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U.S. Navy Halon 1211 Replacement Plan Part I — Development of Halon 1211 Alternatives

D.J. Carpenter
D.P. Verdonik
P.J. DiNenno

Hughes Associates, Inc.
Baltimore, MD

F.W. Williams

Navy Technology Center for Safety and Survivability
Chemistry Division

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*Hughes Associates, Inc.
Baltimore, MD

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13. ABSTRACT (*Maximum 200 words*)

A review and analysis was performed on past and on-going efforts to develop Halon 1211 alternatives. Since 1985, the U.S. Air Force (USAF) has sponsored the majority of the work. The approach has been to develop an agent that would perform the same as Halon 1211 and be suitable for use directly in the existing Halon 1211 hardware, i.e., the drop-in approach. To date, no agents have successfully met the drop-in requirements, and no alternative clean agent has been approved for military, aviation firefighting.

It is recommended that a new approach be pursued that is based on the development of firefighting and other operational requirements. Specific tests based on the requirements need to be established and specific pass/fail criteria developed to evaluate commercially available agents.

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U.S. NAVY HALON 1211 REPLACEMENT PLAN
PART I - DEVELOPMENT OF HALON 1211 ALTERNATIVES

1.0 INTRODUCTION

1.1 Background

The U.S. Navy and the U.S. Marine Corps (USMC) currently use five firefighting agents for suppressing fires on flightlines and flightdecks: water, Aqueous Film Forming Foam (AFFF), Halon 1211, potassium bicarbonate (PKP), and carbon dioxide (CO_2) [NATOPS, 1994]. While each of these agents is potentially effective for flammable liquids and other combustibles typically encountered on flightlines and flightdecks, each has advantages or disadvantages for a particular application. AFFF and water are the primary agents while PKP, Halon 1211 and CO_2 are secondary agents used with the primary agent or alone. The secondary agent is used alone in those situations where the primary agent is not the best choice. It is used in combination with the primary agent when increased effectiveness may result. While AFFF is very effective in fighting pool fires and providing cooling, it is limited in fighting three-dimensional and deep seated, hidden fires. The three secondary agents are better than AFFF in fighting three-dimensional fires and hidden fires but do not provide effective cooling or burn-back protection.

An important distinction among the five agents is the potential for causing collateral damage. Halon 1211 is recognized as the agent that will cause the least collateral damage. While Halon 1211 and CO_2 may both be considered 'clean,' CO_2 under extreme circumstances may cause collateral damage due to thermal shock or electrostatic discharge. PKP and AFFF are not clean agents and may cause considerable collateral damage. For this reason, Halon 1211 has become the agent of choice in many aviation firefighting applications. The ability to reduce or eliminate collateral damage has been shown to be particularly important for engine fires and

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internal electrical fires. The aircraft may be placed back into service more quickly and at a lower cost when solely Halon 1211 is used to extinguish the fire [Leonard et al., 1992].

Halon 1211 was not the first clean, halocarbon agent to be used for aviation firefighting. Chlorobromomethane (CB), also known as Halon 1011, was used by the U.S. Air Force (USAF) as a streaming agent as early as the 1970s for flightline firefighting. Halon 1011 demonstrated the ability to limit collateral damage; however, it had corrosion and toxicity properties that were less than ideal. In the latter 1970s, the USAF sponsored testing of Halon 1211 as a replacement for Halon 1011 [Chambers, 1977]. Halon 1211 was shown to possess the same positive attribute in limiting collateral damage but was much less toxic and corrosive than Halon 1011. The USAF sponsored work and the experience with Halon 1211 in Europe led to the recommendation to replace Halon 1011 in flightline extinguishers [Novotny et al., 1975]. Although no definitive literature source has been found that delineates how the 150 pound capacity was determined, there is anecdotal information available [Chambers, 1977; Burns, 1996; Huston, 1996a]. (A more in-depth analysis will be reported under Part II – Halon 1211 Requirements Review.)

1.2 Halon 1211 on Flightline

The Navy began to incorporate Halon 1211 into flightline firefighting as early as 1977 when Twin Agent Units (TAUs) with AFFF and Halon 1211 were purchased [Rout, 1997; NAVFAC, 1996]. Soon after, Halon 1211 150 pound, wheeled, flightline extinguishers were purchased by the Navy and Air Force. The 150 pound units are intended to provide first aid attack of fires by maintenance and operations crews. Halon 1211 was also placed within crash Fire Rescue (CFR) vehicles such as the P-19. The decision to require 500 pounds of Halon 1211 on CFR vehicles appears to be based on what might fit rather than determining a precise quantity required to meet a particular fire threat. Within the military CFR vehicles 500 pounds was found to fit in the space previously used by PKP [Darwin, 1996-1997].

1.4 Environmental Issues

During the same time period that the Navy was increasing its reliance on Halon 1211, the international environmental community was linking the use of chlorofluorocarbons (CFCs) and halons to the destruction of the stratospheric ozone layer. The first international agreement was the Vienna Convention for the Protection of the Ozone Layer, signed in 1985. The Vienna Convention requires signatories to take appropriate measures to comply with its provisions including all protocols in force to protect against human activities that modify the stratospheric ozone layer. The major protocol under the Vienna Convention is the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987. At present, there are 156 Parties to the Protocol. The Protocol has been amended twice. The first Amendments to the Protocol were enacted in 1990 during a meeting in London and are hence termed the London Amendments. In 1992, the Copenhagen Amendments were adopted. Under the Copenhagen Amendments, production of Halon 1211 ceased in the US (and the rest of the developed nations) on 1 January 1994.

In the U.S., the Protocol was ratified by the Senate in 1988. The status of the Protocol as an International Treaty means that it takes precedence over national law. For example, Title VI of the Clean Air Act Amendments of 1990 (CAAA) requires that the more stringent control measures listed within the CAAA or the Protocol must be followed; the Environmental Protection Agency (EPA) has the responsibility to administer the regulations to adjust the control measures to ensure, as a minimum, compliance with the Protocol.

1.5 Halon 1211 Use and Availability

As a consequence of the Montreal Protocol, the Navy, and all other users of Halon 1211, must rely on and share the quantities of Halon 1211 currently in existence. Recent actions under the Montreal Protocol have been aimed at determining the quantities of halons required to meet fire protection needs versus the quantities available. Surpluses of Halon 1211 may be targeted for

In 1982, the FAA performed tests to qualify Halon 1211 as an acceptable alternative to PKP as a secondary agent for flightline CFR operations. These tests proved that Halon 1211 performed adequately and was subsequently approved for use. The FAA also came across the same 500 pound requirement by a different route. It appears that the 500 pound requirement was derived from an analysis of how much agent could be carried by a standard ¾ ton pickup truck [Wright, 1995].

The National Fire Protection Association (NFPA) committee 403 published the "Standard for Aircraft Rescue and Firefighting Services at Airports" in 1988 [NFPA 403, 1988]. Minimum extinguishing agent quantities and discharge rates were provided for the primary and secondary agents based on the airport category. Halon 1211 and PKP were given a one to one parity with respect to both agent quantities and discharge rates. There does not appear to have been any specific tests performed or referenced in the NFPA committee decision flight [Darwin, 1996-1997]. The latest, 1993, version of NFPA 403 provides the same requirements for PKP and Halon 1211 as the 1988 version [NFPA 403, 1993].

1.3 Halon 1211 on Flightdecks

Halon 1211 was introduced on the flightdeck of U.S. Naval vessels in the mid-1980s as a result of the crash of an EA-6B aircraft on the USS Nimitz [Carhart et al., 1987]. AFFF, PKP and Halon 1211 were evaluated against a standard debris pile fire developed by the Naval Research Laboratory (NRL) [Carhart et al. 1987 and Leonard, et al., 1992] to simulate the fire threat encountered on the USS Nimitz. Based on the work performed by NRL, Halon 1211 was chosen as the secondary agent to AFFF for flightdeck firefighting. The flightdeck firefighting vehicle, P-16, was retrofited to provide 400 pounds of Halon 1211 in addition to the on-board AFFF. As with the flightline CFR vehicles, the decision to require 400 pounds of Halon 1211 appears to be based on the space available within the P-16 vehicle [Darwin, 1996-1997].

mandatory collection and destruction. These actions may serve to reduce further the long-term availability of Halon 1211.

Commencing in 1993, the Department of Defense (DOD) established a strategic reserve of Halon 1211 to supply the needs of the services in lieu of relying on production. The quantities of Halon 1211 purchased, in supply and used were not tracked in the logistics system. Local purchases at dozens of locations hampered the best efforts to get precise data. Best estimates were developed to determine the quantities of Halon 1211 required for the Reserve [DDLA, undated]. The major source of Halon 1211 to support the field has been the Reserve since 1993. With this main source of Halon 1211, the ability of the logistics community to track Halon 1211 issued to the field has been significantly increased. In addition, other military activities, government agencies and industry have been performing research, development, test and evaluation (RDT&E) to develop and prove-out technologies to replace Halon 1211. Recent changes within the Montreal Protocol, technology developments and availability of additional Halon 1211 logistics data provide both the need and opportunity to reevaluate the continued use of Halon 1211.

The work covered in this entire effort will be performed and reported in four parts: (1) Halon 1211 Alternative Development Status, (2) Halon 1211 Requirements Review, (3) Halon 1211 Mission Critical Reserve Evaluation and (4) Halon 1211 Replacement Program Plan. The work covered in this effort is for Part I – Halon 1211 Alternative Development Status.

2.0 OBJECTIVE

The overall objective of the entire effort is to provide input for a detailed Halon 1211 Replacement Program Plan. The purpose of the program plan is to ensure that the Navy is

adequately prepared to support aviation CFR operations on flightlines and flightdecks through continued use of Halon 1211 and/or replacement technologies.

To meet the overall objective, the plan will be based on (1) an evaluation of (a) the method and (b) development of replacement technologies; (2) an assessment and delineation of fire protection operational requirements that currently use Halon 1211; (3) quantification of the amount of Halon 1211 within the Navy, including the Reserve, available to meet the requirements; (4) an estimation of the Halon 1211 needed to meet the fire protection requirements and (5) assessment of policy and procedural changes that may be implemented to reduce the required Halon 1211. The work presented in this report covers item (1): the evaluation of the method and development of Halon 1211 replacement technologies.

The objective for the work performed under Part I was to review and evaluate previous and on-going RDT&E efforts to develop Halon 1211 alternatives and replacements. The intent was to determine when the U.S. Navy could expect that suitable Halon 1211 replacements/alternatives will be commercially available. The applications that the U.S. Navy would consider for a new agent include flightline and flightdeck firefighting, and internal aircraft use.

3.0 APPROACH

3.1 Drop-in Agent Approach

Two different approaches may be used to perform the reevaluation of continued Halon 1211 use in developing the Replacement Plan. The first approach starts with the premise that every application that currently uses Halon 1211 must continue to use a Halon 1211 like replacement. This type of thinking has lead to the 'drop-in' philosophy where the one new agent must work in all current Halon 1211 equipment. The new drop-in agent would have all of the

positive attributes of Halon 1211 but would not have the negative environmental impacts. It essentially defines the requirement as Halon 1211. It defines the purpose as replacing Halon 1211 and sets the performance goal at the level of Halon 1211. This approach limits the ability to create significant advances in technologies. The lure of the drop-in approach is that, if it is successful, there will be limited logistical and cost impacts. The major disadvantage is that, if it is unsuccessful, Halon 1211 will be the only agent available to meet the firefighting need with current equipment.

3.2 Systems Engineering Approach

The second approach starts with the premise that each application that currently uses Halon 1211 can be defined by firefighting requirements. Instead of assuming that the requirement is to replace Halon 1211, it places the need at performing the required firefighting. It requires understanding and defining the firefighting requirements for each application. This philosophy places the emphasis on the systems engineering required to meet the threat and not solely on the agent itself, i.e., a performance specification. Tests need to be developed that adequately measure the ability of the system to meet the documented requirement. The disadvantage of the systems engineering approach is that it is inherently harder to perform than the drop-in approach. It requires a better understanding of the operational and technical requirements. The major advantage is that a wider range of technologies can be explored. This approach will also lead to a better understanding of the science and engineering involved, and enhances the ability to develop significant advances in technology.

Several organizations have shown great success with the systems engineering approach in resolving Halon 1301 applications. The Navy has approved inert gas generators in the V-22 and F/A-18E/F, and the Army has approved FM-200 in the RAH-66 for engine nacelle fire protection. CO_2 portables, water mist and dry chemicals are all replacing Halon 1301 in various applications. All of these successful alternatives would have been eliminated from consideration using the drop-in approach. To date, no drop-in agent has been implemented in any fire protection application.

Emphasis has been placed on the systems engineering approach in performing and reporting this work.

3.3 Assignment I - Halon 1211 Alternative Development Status

A review of the open literature was performed to identify all of the past and on-going work performed on Halon 1211 alternatives and replacements. For the purposes of this report and to be consistent with the majority of the literature, the term alternative is used to signify a not in-kind technology, and replacement to signify an in-kind technology. For example, the use of a dry chemical powder to replace the Halon 1211 gas/liquid is considered an alternative whereas the use of a halocarbon gas/liquid is a replacement. The open literature sources included FIREDOC at the National Institute for Standards and Technology (NIST), the National Technical Information Service (NTIS) and UNCOVER at the University of Maryland. Internal Hughes Associates, Inc. documents mainly from open literature sources were also searched. The search included work by the U.S. Air Force (USAF), Federal Aviation Administration (FAA), United Kingdom (UK) Civil Aviation Authority (CAA), NIST and commercial industry. Additional information was obtained from non-open sources, e.g., internal reports, when identified and obtained. The specific items to be addressed follow [Leach, 1996]:

a. Review the entrance requirements to the test matrices with explanations for the test chemicals;
b. Review of the test parameters providing rational for individual test parameters and the basis for extremes;
c. Assessment of the test equipment and methodologies used including applicability and effectiveness;
d. Review of collected data including past test successes and failures, and the reasons for each;
e. Review of the success criteria;

f. Compilation of the lessons leaned and any recommended program modifications; and

g. Analysis of the efforts outside the Navy.

4.0 OVERVIEW OF LITERATURE REVIEW

The review of work to find an alternative to Halon 1211 falls into three general areas: (1) Research, Development, Test and Evaluation (RDT&E) performed by the USAF, (2) T&E performed by the FAA and other national aviation authorities, and (3) T&E performed by commercial industry. However, the clear majority has been performed, or sponsored, by the USAF. In some cases, the Halon 1211 efforts were combined with Halon 1301 work. For the most part, only the Halon 1211 related work is discussed.

The effort to find alternatives for Halon 1211 consists of many different projects, occurring simultaneously at several locations. In performing the review and analysis, it became necessary to construct groupings of the different projects to better understand the work. Each major grouping will be called a Program. In some cases, the name of the Program may be different from that presented in the literature. This was based on the recognition that the USAF work evolved due to changing targets. The USAF program once initiated confronted a quickly changing set of environmental requirements as new environmental scientific discoveries took place [ARA, 1998]. As a result, changes in goals were made as the project was underway to keep pace with the changing environmental science and regulatory actions. To assist in understanding the interrelation of the programs and projects, a time line is presented first. This is also shown graphically in Figure 1. Following the time line, a detailed review of each program is presented.

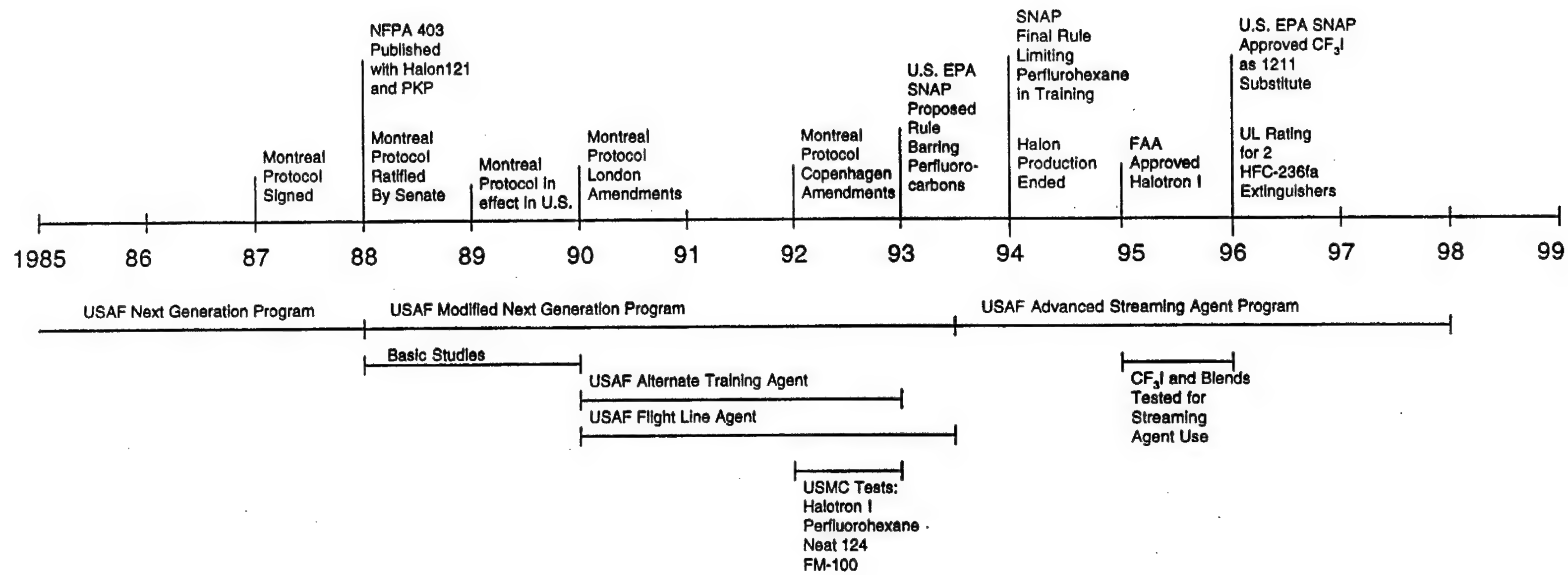

Figure 1. Time Line for Halon 1211 Replacement

4.1 Time Line

Beginning in 1985, the USAF led a research effort for the USAF and Navy to develop a new streaming agent with improved three-dimensional and toxicity properties over Halon 1211 [Tapscott et al., 1987a; 1987b; 1987c; 1987d]. The USAF "Next Generation Program" (NGP) included three primary efforts: basic studies, laboratory/medium-scale testing and full-scale testing. Concurrent with their other on-going work, the USAF sponsored NIST to perform two projects. The first project was to develop a comprehensive plan to identify and qualify new fire suppressants [Gann et al., 1991a]. The work began in 1987 and was mainly driven by the USAF.

As the NIST and other NGP work developed, concern over the environmental impacts of halons and the possibility of regulatory restrictions, particularly in training, drove the need to alter the program. The original program was modified in 1988 to include environmental requirements [Tapscott et al., 1987e]. The second NIST project was performed at about the same time. The intent was to develop the list of potential candidates to explore as halon alternatives that incorporated the 'new' environmental requirements [Gann et al., 1991b].

The altered USAF program consisted of three separate efforts. For the purposes of clarity in this review, the modified program will be considered a continuation of the NGP and will be termed the Modified Next Generation Program (MNGP). Each of these three efforts consisted of many projects which were run concurrently. The first effort ran from 1988 through 1990 [Tapscott et al., 1989a; 1989b; 1989c; 1991a]. It was aimed at continuing the basic science studies begun under the original program. The goal of the second effort was to find a suitable training agent to replace Halon 1211 [Tapscott et al., 1990a; 1990b; 1990c; 1990d]. It began in 1988 and was combined with the third effort in approximately 1993. This third effort was aimed at finding a suitable alternative for flightline use [Tapscott et al., 1991b; 1995; DDRE, 1993]. It also began in 1988 and was completed in 1993.

In 1992, the U.S. Marine Corps tested Halotron I, perfluorohexane, and several other agents as potential flightline extinguishing agents [MCAS, 1992; Pignato et al., 1993; Huston, 1996a]. Soon thereafter, in approximately 1993, "final" full-scale testing was performed by the USAF on the two leading candidates, Halotron I and perfluorohexane [Cowherd, 1995; Lee and Tapscott, 1992; 1993; Rochefort et al., 1993; Wright, 1995]. Some of the testing was sponsored by the FAA. As a result of the full-scale testing, the USAF chose perfluorohexane and the FAA chose Halotron I as the leading candidate for a Halon 1211 replacement [DDRE, 1993; Wright, 1995]. In 1994, the Environmental Protection Agency (EPA) under the Significant New Alternatives Policy (SNAP) program, placed restrictions on the use of perfluorohexane in recognition of its long atmospheric lifetime [EPA, 1994]. Due to the environmental concern of global warming, atmospheric lifetime and the proposed restrictions, perfluorohexane was not introduced as a Halon 1211 replacement by the USAF [ARA, 1998]. In 1995, Halotron I was recommended by the FAA as a suitable alternative to Halon 1211 [Wright, 1995].

After the full-scale testing in 1993, the USAF began development of a follow-on research program [DDRE, 1994; DDRE 1996; Skaggs et al., 1993; DDRE, 1995]. A guiding premise in developing the follow-on research was that all of the available or soon to be available agents had long atmospheric lifetimes, were considered too toxic, had regulatory restrictions or required 2 to 3 times the Halon 1211 on a weight/space basis [ARA, 1998]. The goal of the Advanced Streaming Agent (ASA) Program was to overcome the toxicity and environmental regulatory concerns associated with the then commercially available agents. It was initiated to explore several promising families of laboratory-scale chemicals that would be more space and weight effective than the commercially available candidates [DDRE, 1994; DDRE, 1995; DDRE, 1996]. The program is ongoing and based on the available literature is scheduled to be completed in 1998. Although several proposed alternatives were initially identified through this R&D, no fire extinguishing agent has been found "acceptable" or approved for use by the USAF for flightline fire extinguishers [Tapscott and Skaggs, 1994; Tapscott et al., 1996a; 1996b].

In 1995, the United Kingdom (UK) Civil Aviation Authority (CAA) sponsored a study to develop a standard test method to quantify the capabilities of the required Halon 1211 portable for hidden fires [Chattaway, 1995]. Although not originally a requirement when the Halon 1211 portables became a required item on aircraft, the consensus was that this capability would be a requirement for a Halon 1211 replacement. The standard would be used by the FAA and other national regulatory agencies. Alternative agents were evaluated using the developed test method. To date, only Halon 1211 is "approved" for use on board commercial aircraft.

Currently, extinguishers using Halotron I, FE-36, and FM-200 are commercially available and have received Underwriters Laboratories, Inc. (UL) ratings. In addition, commercial industry has obtained the EPA SNAP list approval for FE-241, NAF P-III, Triodide, and CEA-614 for streaming applications [Huston, 1996b].

5.0 DETAILED LITERATURE REVIEW

5.1 USAF Next Generation Program (1985 - 1988)

The USAF Next Generation Program (NGP) was the initial effort to develop concepts for a next generation fire suppressant for multi-dimensional fires. The work began in 1985. While it was generally recognized that halons have excellent performance on three-dimensional fires and are clean agents, they do not provide protection against re-ignition. In addition, the USAF acknowledged that halons had toxicity problems and may possess unacceptable environmental impacts [Tapscott et al., 1987a].

5.1.1 Requirements

A list of the required characteristics was developed for the program [Tapscott et al., 1987a].

- To ensure readiness the agent must be clean. Undamaged aircraft in or near a fire extinguishment operation must be immediately available for use. Excessive manpower must not be diverted to cleanup following a fire, particularly during wartime. Electrical components not damaged by the fire must remain usable.
- Exhibit acceptable toxicity and environmental impacts.
- Have good deliverability for streaming applications.
- Be able to secure a fuel against flashback.
- Exhibit good dimensionality.

This list would appear to be the "operational requirements" for a new agent. The requirements were developed through evaluation of the existing performance capabilities of Halon 1211 [ARA, 1998]. In the early NGP, the researchers did not concern themselves with stringent protocols and precisely established requirements. In part, this is because it was expected that an answer to the Halon 1211 replacement problem was "just around the corner." In addition, it was felt that many of the early replacement agents might be "drop-in" agents for many of the applications then served by Halon 1211. Tests were established to show that the proposed candidates would work as drop-in solutions.

In order to provide communication flow between researchers, industry and other military organizations, several informal meetings and conferences were held early in the NGP [ARA, 1998]. Subsequent review and status meetings became formalized through what is now the Halon Options Technical Working Conference held each year in Albuquerque, NM. During one of the early meetings held at the University of New Mexico, the attendees toured the fire test site, test apparatus and test burns. It was the consensus at the time that these tests were sufficient to test and evaluate potential replacement chemicals. As the tests continued, it became more and more apparent that a drop-in agent would not easily be found.

During the three years of this effort, many different projects were undertaken. The effort ranges from basic studies in fire dynamics through full-scale testing [Tapscott et al., 1987a; 1987b; 1987c; 1987d; 1987e]. The basic research focused on developing and analyzing fire

physics, chemistry and engineering information for flame structure, fire modeling, combustion reactions, oxidation kinetics, combustion thermodynamics and fire suppression. Emphasis was placed on both known and hypothesized mechanisms of fire extinguishment, and on known fire-inhibiting agents. New agents were proposed based on both known and postulated fire suppression mechanisms.

5.1.2 Screening

Early in the NGP, it was believed by the USAF researchers that halons and related agents, e.g., halocarbons, offered the best prospects for meeting these program requirements, particularly in the near-term [Tapscott et al., 1987a]. Emphasis was placed on halons and halon-like suppressants that act through chemical mechanisms. The research plan included work with a cup burner and small pan fires. These tests permitted a rapid and cost effective evaluation of the efficacy of a streaming agent [ARA, 1998] although the relationships of these tests to full-scale performance in streaming applications is unknown. Other analytical techniques such as Laser Raman Spectral studies were also explored [Tapscott et al., 1987a]. The initial list of agents, developed from the basic studies, follows.

- Iodinated organics with an emphasis on high molecular weight materials.
- Halogenated unsaturated hydrocarbons.
- Mixtures of halons with hydrocarbon fuels.
- Halons with methoxy and other polar substituents.
- Thermally degradable compounds.

5.1.3 Laboratory-scale Testing

The candidate agents identified were tested for extinguishment concentrations using a standard cup burner apparatus as a screening tool [Tapscott et al., 1987b]. The researchers recognized cup burner data examined only extinguishment by chemical processes. They

recommended that extinguishment data during discharge of halon-like agents should receive high priority in the future work to encompass physical parameters. The physical characteristics of a compound were felt to be as important as the chemical processes for a streaming agent.

The testing resulted in the development of a relative ranking of suppression ability of the candidate agents [Tapscott et al., 1987b]. Based on the ranking, it was recommended that hydrochlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs), and their blends continue through the evaluation process. Table 1 lists the types of chemicals and blends studied [Tapscott et al., 1987b; 1987c]. It was recommended further that studies of flame-agent interactions with Raman or other spectroscopic tools are sufficiently complex that the basic spectroscopic studies should be reported under separate work [Tapscott et al., 1987b].

Table 1. Candidate Agents for Next Generation Program [Tapscott et al., 1987b; 1987c]

CFC-114 ($C_2F_4Cl_2$)	CFC-114 (50%) - Halon1211 (50%) ($C_2F_4Cl_2$ - CF_2BrCl)
HFCF-22 (CHF_2Cl)	CFC-11 ($CFCl_3$)
CFC-12 (CF_2Cl_2)	

To better define the small-scale fire suppression testing, the researchers developed a new apparatus [Tapscott et al., 1987c]. The Laboratory-scale Discharge Extinguishment (LSDE) testing apparatus was designed and its performance evaluated using Halon 1211, HCFC-22, CFC-11 and CFC-12. These and other agents were tested to extinguish JP-4 fuel fires in a six-inch square pan. The results indicated that a mixture of CFCs and/or HCFCs could provide an acceptable training agent, if the boiling point were sufficiently high to offset the inherently lower fire suppression ability of these materials. The small-scale discharge tests verified that agent deliverability is highly dependent on boiling point. Their conclusion was that the boiling points of

these candidate agents should be high enough to offset the lower fire suppression capability. The study concluded that mixtures of CFCs and/or HCFCs appear to be acceptable candidates and recommended that the testing be continued [Tapscott et al., 1987c]. The researchers further recommended that a survey of generally available CFCs and HCFCs be conducted with particular emphasis on toxicity and environmental characteristics.

Efforts were directed at chemicals that would be available in the near term [Tapscott et al., 1987d]. Halocarbons, i.e., HCFCs, perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs), that were also under consideration as CFC replacements, were the major focus for T&E efforts. Other chemicals were also included in the more basic R&D studies with the intent to identify longer term candidate agents. The longer term candidates provided a "fall-back" position should the near-term candidates not meet the program goals [ARA, 1998].

5.1.4 Medium-scale Testing

Medium-scale fire extinguishment tests were performed with the candidate agents identified [Tapscott et al., 1987d]. These tests consisted of 0.91, 0.37, 2.6 and 13.9 m^2 (1, 4, 28 and 150 ft^2) outdoor pit (pool) fires out with "off-specification" JP-4 fuel and a 10-second pre-burn time.

5.1.5 USAF NIST Sponsored Work

The USAF sponsored work by NIST to perform a preliminary screening evaluation [Gann et al., 1991a]. The evaluation focused on currently available screening methods. It resulted in the review of screening procedures for fire suppression, ozone-depletion potential (ODP), global warming potential (GWP), metal corrosion, materials compatibility, storage stability and toxicity.

As part of the screening evaluation, NIST began to formulate a comprehensive plan to identify and qualify new fire suppressants. When started in 1987, it was mainly driven by the

USAF and is cited as part of the USAF work [Floden, 1992]. By 1989, a group of industrial and Federal agencies joined the effort.

5.2 Modified Next Generation Program (1988 - 1993)

In 1988/89, it became apparent that the on-going work with CFCs must be altered because of environmental requirements, particularly for ozone-depletion. This would coincide with the signing of the Montreal Protocol and the ratification of the Protocol by the U.S. Senate. Based on their on-going work to assess available toxicity indexes and environmental data, the researchers concluded that the low toxicity and high volatility of CFCs and halons makes the environmental impacts of these materials, other than stratospheric ozone depletion and global warming, relatively minor [Tapscott et al., 1987e]. Therefore, in the search for halon and CFC-like alternatives (i.e., halocarbons), the researchers believed that the only environmental requirements were global warming and ozone-depletion. As a result of this decision, it was recommended that a computerized database of halocarbon properties be developed. The database would provide an easy method to screen candidate agents for (1) predicting extinguishment capability from molecular formulas for halocarbons, (2) comparison of toxicity indices, (3) investigating the availability of agents available in large volumes either as products or in the process stream and (4) developing rapid and economical prediction of ODP from molecular structures.

It was recognized that a new work plan was needed to define the approach for a program to develop Halon 1211 alternatives [Tapscott et al., 1987e]. The approach was based on the following rationale.

- No single problem and no single solution exist.
- Approaches must be goal-oriented and directed.
- A parallel-path approach is required to meet USAF needs.

The plan tried to recognize that many different fire protection needs exist [Tapscott et al., 1987e]. The challenge was considered to be complicated because numerous applications of Halon 1211 would need to be solved. These areas included fire suppression for crash, fire and rescue (CFR) operations, protection for computer facilities, protection for aircraft shelters, on board fire suppression systems for aircraft and effective firefighter training. Moreover, the challenge of halon restrictions encompassed such problems as public concern over environmental impact of USAF operations and the politics of halon usage in support of foreign-based USAF forces.

The work plan presented three possible paths and suggested that the USAF work must consider all three [Tapscott et al., 1987e]. The researchers did not believe that any single path would solve the multitude of Halon 1211 replacement needs. The three paths believed to be needed were (1) use new engineering methods based on risk and cost/benefit analysis to evaluate the need for a clean agent such as Halon 1211 or a replacement; (2) develop new or modified hardware that can decrease the reliance on halon use, thus decreasing the reliance on halon; and (3) develop an alternative or replacement agent. For the most part, it appears from the literature that the clear majority of work was placed on the third path. An evaluation was performed of the need for a clean agent as suggested in the first approach [Leonard et al., 1992]. This evaluation occurred during the latter portion of the MNGP [ARA, 1998].

The researchers reported that in the past, Halon 1301 and 1211 were developed and uses were subsequently found [Tapscott et al., 1987e]. They felt that a similar situation is unlikely to meet the needs of the USAF. It was postulated that one or two all-purpose agents, having all the important properties equal to those of existing halon fire extinguishers, are unlikely to be found in the foreseeable future. A group of alternative, clean, halon-like chemicals, varying according to application, was believed to be a more realistic target. Based on this analysis, two USAF needs were identified as particularly critical: aircraft ground firefighting (CFR for flightline) and firefighter training. The MNGP was developed to resolve these two major needs.

5.2.1 MNGP - Halocarbon Database

One of the first efforts under the MNGP was to carry out the recommendation to develop a database to provide an easy way to identify new candidates [Tapscott et al., 1987e]. The NMERI Halocarbon Database was initiated. The potential candidate agents were separated into three groups: short-term, medium-term and long-term options based on available toxicity data and the near-term availability of the agent [ARA, 1998]. These are provided in Table 2 [Tapscott et al., 1990a]. Estimation algorithms were developed for ODP and fire extinguishment concentrations [Tapscott et al., 1987e]. A list of promising candidate agents was developed based on ODP, boiling point and fire suppression concentration predictions. This fire suppression prediction algorithm was validated using cup burner data.

Table 2. Group 1 Candidates [Tapscott et al., 1990a]

PFC - 14	CF_4	HFC-134a	($C_2H_2F_4$)
HCFC-21	($CHFCl_2$)	HCFC-140a	($C_2H_3Cl_3$)
HCFC-22	(CHF_2Cl)	HCFC-141b	($C_2H_3FCl_2$)
HCFC-123	($C_2HF_3Cl_2$)	HCFC-142b	($C_2H_3F_2Cl$)
HCFC-123b1	($C_2HF_3Cl_2$)	HFC-143a	($C_2H_3F_3$)
HCFC-124	(C_2HF_4Cl)	HFC-152a	($C_2H_4F_2$)
HCFC-132	($C_2H_2F_2Cl_2$)	PFC-614	(C_6F_{14})

At about this same time, NIST was also tasked by the USAF to develop a new list of potential chemicals to explore [Gann et al., 1991b]. A preliminary screening of chemical families was used to develop a list of approximately one hundred chemically diverse gases or liquids from a wider range of compounds. These chemicals covered a range of chemical and physical principles thought to affect flame suppression capability. Basic information on each of the selected compounds was compiled, and the initial screening for each was completed. The screening process focused on fire suppression and ODP. It was acknowledged that this decision required that other important characteristics be de-emphasized. The most critical of these was toxicity.

5.2.2 MNGP - Basic Studies

A continuation of the basic studies continued from 1988 through 1990. The first effort was performed from 1988 through 1989 [Tapscott et al., 1989a; 1989b; 1989c]. It focused on basic laboratory studies involving the use of laser Raman spectroscopy. The effort was designed to determine the effect when Halon 1301 penetrates a flame front. Halon jets impinged on flame boundary layers so that the spatial distribution of the resulting reactions could be determined. Laser Raman spectrometry, mass spectrometry and fluorescence techniques were used as probes [Floden, 1992]. The overall efforts focused on furthering the understanding of fundamental flame extinguishing mechanisms of halons and verifying the applicability of experimental techniques.

The second part of the basic studies was performed from 1989 to 1990 [Tapscott et al., 1991a]. The initial studies of the fire reaction of halon showed that better data might be attainable by the use of photoionization techniques. These were used to determine the role of molecular association or clustering in combustion and suppression, and to develop new approaches to fire suppression. Molecular clusters of halon, halon-like materials, oxygen and fuels were created and photoionized. The resulting products were analyzed by mass spectrometry. Initial clusters were characterized from these data. It was reported that the overall efforts focused on furthering the understanding of fundamental flame extinguishing mechanisms of Halon 1301.

5.2.3 MNGP – Alternative Training Agents (1988-1992)

The goal of this effort was to develop an alternative agent for use only in training firefighters [Floden, 1992]. This low ODP agent would have very similar properties to Halon 1211. It would behave enough like Halon 1211 that firefighter training would not be compromised. Halon 1211 would have been used to fight actual fires. The results of this effort were reported as four distinct projects [Tapscott et al., 1990a; 1990b; 1990c; 1990d].

5.2.3.1 Screening

The first step in the effort was to develop the list of candidate compounds for further testing [Floden, 1992]. The NMERI Halocarbon Database and a detailed literature review were used to develop the list of candidate agents [Tapscott et al., 1990a; ARA, 1998]. Algorithms were built into the computer database to estimate unmeasured properties. Candidate agents were divided into three groups. Group 1 was near-term candidates that were defined as (1) produced in bulk in the recent past, (2) in production [at that time], or (3) being developed for near-term bulk production, AND for which significant toxicity studies have been performed or were in progress and indicated acceptable toxicity. The toxicity data should be available through chronic studies. Group 1 candidates came from HCFCs, PFCs and HFCs as shown previously in Table 2. Group 2 contained intermediate-term chemicals that were expected to have low toxicity but only a limited amount of toxicity information was available. Group 2 candidates included those HCFCs, PFCs and HFCs that were not part of Group 1. Group 3 was considered far-term chemicals. They were expected to have very good or even superior fire extinguishing capabilities, but very little or no toxicity data were available. HBFCs, highly chlorinated halocarbons, and unsaturated compounds fell into this group.

Several chemicals were extracted from the literature or chosen through discussions with industry [ARA, 1998]. The chemicals were qualitatively screened according to ODP, GWP, toxic effects, stage of toxicity testing, flame suppression concentration, cost and physical properties of delivery and flame extinguishment [Tapscott et al., 1990a].

Group 1 compounds were not excluded because they were poor flame suppression agents based on cup burner testing [Tapscott et al., 1990a]. The researchers believed that a small decrease in effectiveness would be acceptable for a large gain in environmental safety. It was felt that improved firefighting techniques would result from a less effective training agent. Compounds were chosen for near-term candidates because they were known to have significant toxicity testing completed or they were available in large quantities sufficient for field-scale testing

[ARA, 1998]. Table 3 provides the list of chemicals recommended for laboratory-scale testing [Tapscott et al., 1990a].

Table 3. List of Agents Recommended for Laboratory-scale Testing [Tapscott et al., 1990a]

HCFC-123 (neat)
HCFC-123 blended with HCFC-22
HCFC-123 blended with HCFC-124
HCFC-123 blended with HCFC-134a
HCFC-123 blended with HCFC-141b
HCFC-123 blended with HCFC-142b
HCFC-123 blended with HCFC-152a
HCFC-123 blended with PFC-318

5.2.3.2 Laboratory-scale

The researchers employed laboratory-scale tests to screen large numbers of chemicals that may be expensive and/or not commercially available in bulk [Tapscott et al., 1990b]. Work was performed on the further development of cup burner tests and the LSDE apparatus. The intent was to reduce candidates before expensive and time consuming medium and full-scale testing. It was determined that while cup burners are excellent for estimating the effectiveness of an agent in total flooding applications, they are less useful in determining the fire extinguishing capability of streaming agents and applications. They reported that previous testing performed at NMERI had shown that the physical properties related to streaming, fire penetration and fuel securing are at least as important as cup burner extinguishment concentrations in determining the fire extinguishing capability of streaming agents.

The Group 1 candidates were evaluated in the cup burner [Tapscott et al., 1990b]. The pure chemicals and several blends were selected and evaluated using the LSDE apparatus. To minimize variability, many discharge tests needed to be performed with each candidate agent. It

was also recognized that a standard test protocol was needed to reliably compare the effectiveness of different agents. It was concluded that the LSDE apparatus correlated well with streaming agent performance for Class B fires in medium and full-scale tests. Based on the results of the laboratory testing, neat HCFC-123 was chosen from cup burner data, and HCFC-123 blends were chosen from LSDE data as the candidate agents to continue in medium-scale testing. These are provided in Table 4.

Table 4. List of Agents Recommended for Medium-scale Testing [Tapscott et al., 1990b]

Based on Cup Burner	Based on LSDE
HCFC-123 (neat)	HCFC-123 (neat)
	HCFC-124 (neat)
	HCFC-123 blended with HCFC-22
	HCFC-123 blended with HCFC-124
	HCFC-123 blended with HCFC-141b
	HCFC-123 blended with HCFC-142b
	HCFC-123 blended with HCFC-134a
	HCFC-123 blended with HCFC-152a

5.2.3.3 Medium-scale Testing

HCFC-123 and blends with HCFC-22 and HCFC-142b, and mixtures of HCFC-152a and HFCF-141b were tested at medium-scale [Tapscott et al., 1990c]. The series consisted of progressive testing of 0.37 m^2, 3.0 m^2 and 7.0 m^2 (4 ft^2, 32 ft^2 and 75 ft^2) JP-4 fires. The effectiveness criteria were rapid knockdown and initial containment, maintenance of control without flashback or re-ignition, effective extinguishment of large fires and extinguishment without intensification. Those candidates that were considered "favorable" were tested further.

All of the tests were conducted in a fenced wind enclosure constructed of TENAX Riparella mono-oriented net wind fencing. The wind enclosure was constructed as a pair of concentric circles to maximize the wind abatement effect. The enclosure completely surrounded

the test area. The outer fence diameter was 9.1 m (30 ft) for the 0.37 m^2 (4 ft^2) pool fire and 42.7 m (140 ft) for both the 3.0 m^2 (32 ft^2) and 7.0 m^2 (75 ft^2) pool fires. The inner fence diameter was 4.3 m (14 feet) for the 0.37 m^2 (4 ft^2) pool fire and 25.9 m (85 ft) for the 3.0 m^2 (32 ft^2) and 7.0 m^2 (75 ft^2) pool fires. The fence height was 3.05 m (10 feet) and 5.5 m (18 feet), respectively. The pool fires were located within the center of this structure.

Military grade JP-4 was used for all of the tests [Tapscott et al., 1990c]. The fuel was floated on top of a pool of water. Quantities of fuel and water were derived with the intent that (1) a "fully involved" fire would be produced in 60 seconds after ignition and (2) "full intensity" of the fire would be maintained throughout the entire test. The amount of fuel necessary was determined by conducting standard 0.37 m^2 (4 ft^2) and 3.0 m^2 (32 ft^2) fires with known quantities of fuel [Tapscott et al., 1990c]. The fire intensity was measured with a K-Type thermocouple positioned 1 inch above the fuel surface of the 0.37 m^2 (4 ft^2) and 25 cm (10 in) above the fuel for the 3.0 m^2 (32 ft^2) fire. The same ratio of fuel to water was also used in the 7.0 m^2 (75 ft^2) pool fire but not for the 7.0 m^2 (75 ft^2) ring fire. For the 7.0 m^2 (75 ft^2) ring tests, the amount of fuel was decreased by half. It was assumed that fuel could be saved and a reproducible fire, sufficiently long-lived for testing, was still produced. Additionally, it was stated that this condition matched those being used in other USAF testing at Tyndall Air Force Base (AFB).

The test procedure was to ignite the fuel and allow it to burn for 30-60 seconds before applying the candidate fire extinguishing agent [Tapscott et al., 1990c]. The required technique was for the firefighter to approach the fire from the upwind direction, sweep the agent stream in front of the pit to build up agent concentration, and then move the stream into the pit.

The agents were assessed against several test parameters [Tapscott et al., 1990c]. The effectiveness of each candidate agent was determined from (1) the amount of agent required to extinguish the fire, (2) the way the agent reacted to the fire when applied, (3) the amount of effort and time required for extinguishment and (4) the agent flow rate. For the small fires, each agent was treated as a drop-in replacement for Halon 1211 with respect to fill densities, pressurization

and hardware. No extinguisher optimization was performed at this stage of the testing [ARA, 1998]. For the larger fires, a different nozzle was used for the candidate agent to adjust the flow to be more like Halon 1211 [Tapscott et al., 1990c]. Based on the results of the medium-scale testing, two agents were recommended for large-scale testing: neat HCFC-123, and HCFC-123 & HCFC-142b (80:20).

5.2.3.4 Full-scale Testing

Large-scale tests were performed with four agents: neat HCFC-123; HCFC-123 & HCFC-142b (80:20); HCFC-123 & HCFC-142b (70:30) and HCFC-123 & HCFC-22 (80:20) [Tapscott et al., 1990d]. The researchers reported that no guidelines for standard firefighting training scenarios existed within the Air Force as of February 1992 [Tapscott et al., 1990d]. They conducted a survey of several different types of 3-D training apparatus throughout the Department of Defense, industry and research institutions. No standard training apparatus was found. The researchers developed a test designed to simulate a suspended jet engine fire with a fuel line leak [Tapscott et al., 1990d]. Two pool fire tests were also included in the series, 7.0 m^2 (75 ft^2) and 14 m^2 (150 ft^2). The 7.0 m^2 (75 ft^2) pool fire was exactly the same test as previously described in the medium-scale series.

The 14 m^2 (150 ft^2) test was very similar to the 7.0 m^2 (75 ft^2) test. The tests were conducted in the previously described fenced enclosure constructed of the TENAX Riparella mono-oriented net wind fencing [Tapscott et al., 1990d; ARA, 1998]. The enclosure totally surrounded the test area and had an outer fence diameter of 43 m (140 feet), an inner diameter of 26 m (85 feet), and a height of 6.1 m (20 feet). The 14 m^2 (150 ft^2) fire was used for the final evaluation.

The test method for the 14 m^2 (150 ft^2) was very similar to the 7.0 m^2 (75 ft^2) tests. JP-4 fuel was floated on top of water that had been allowed to cool off from the previous testing [Tapscott et al., 1990d]. The fuel was ignited and allowed to burn for 30 seconds before the

agent was applied. The firefighter approached the fire from the upwind direction, swept the agent stream in front of the pit to build up agent concentration, and then moved the stream into the pit. A modified nozzle tip was used for these tests that was shown to 'throw' the candidate agents more efficiently than the standard Halon 1211 nozzle.

An initial 'prototype' 3-D apparatus was developed to simulate a running, 3-D training fire [Tapscott et al., 1990d]. Fuel was sprayed evenly at 57 to 76 ℓpm (15 TO 20 gpm) into a 0.6 m (25 in) pipe and allowed to overflow into the pan. The fire was considered to be quite difficult to extinguish; therefore, Halon 2402 was first used to baseline the fire. Halon 1211 was used to establish a second baseline once the technique for Halon 2402 had been developed. Two candidate agents were tested with this prototype. For the one test each, neither agent could control or extinguish the fire. A new 3-D apparatus was developed.

The final 3-dimensional apparatus was constructed of two barrels and one intake port of a B-52 aircraft engine cowling [Tapscott et al., 1990d]. The barrels were nested one inside the other with strut supports welded to the barrels to keep the inner barrel equidistant from the inner edge of the outer barrel. The inner barrel was a standard 208 ℓ (55 gallon) drum with a diameter of 57 cm (22.5 in) and a length of 91 cm (36 in). The outer drum was an over-pack drum with a diameter of 76 and 91 cm (30 to 36 inches) and a length of 1.1 m (44 inches). The drums were hung from a fabricated swivel mount on a horizontal boom so that the front edges of the barrels were 15 degrees lower than the back edges. A flexible fuel line was run along the boom into a vertically mounted, multidirectional spray bar. The fuel sprayed toward the front, or lower end, of the apparatus and into the inner barrel. A portion of the fuel flowed into the outer barrel through circular holes cut into the bottom of the inner barrel. The remainder of the fuel flowed the length of the inner barrel into the overlapped edge of the outer barrel. Eventually, the fuel overflowed onto a pool of water in the circular containment pit located 1.2 to 1.5 m (4 to 5 feet) below the apparatus. Fuel flow was regulated at 13.3 lpm (3.5 gpm). A circular metal ring, 41 cm (16 in) tall, was placed in the center of the pit to contain the fuel to a 7.0 m^2 (75 ft^2) area.

The conclusion of the Alternative Training Agent work was that the two best candidates were neat HCFC-123, and a blend of HCFC-123 and HFCF-142b (80:20). Only a relative comparison of each agent was made against Halon 1211. No decision was made by the USAF to replace Halon 1211 for fire training with any of the tested agents.

5.2.5 Flightline Agent (1988 - 1992)

Concurrent with the Training Agent Project, the USAF was also performing work to find a suitable agent to replace Halon 1211 on the flightline. The objective of this effort was to develop one or more alternative clean halocarbon fire extinguishing streaming agents to replace Halon 1211 [Floden, 1992]. The replacement agent would need to be "acceptable for use in crash-rescue vehicle agent delivery systems, wheeled portable units and hand-held extinguishers" and have "no current or future use restrictions directed by U.S. Law, International Treaty or Air Force Regulation, and is approved for sale under current U. S. regulatory requirements" [DDRE, 1993].

5.2.5.1 Requirements and Target Criteria

The approach taken was very similar to the Alternate Training Agents work. The candidate agents would be identified based on fire extinguish effectiveness, atmospheric lifetimes, available toxicity information, market availability and various other items concerning environmental impacts or occupational hazards [Floden, 1992]. The following target criteria were established for candidate replacement agents [Tapscott et al., 1991b].

- Agent leaves no residual upon evaporation.
- No major changes in Air Force equipment be required for storage, transfer or delivery (i.e., drop-in replacement).
- Have an Ozone Depletion Potential (ODP) of 0.05 or less.

- Acute Toxicity (as determined by rat 4-hour LC_{50}) shall be equal to, or better than, the halon being replaced.
- Other environmental impacts be equal to, or less than, that of the halon being replaced.

Sometime after the development of the initial set of target criteria changes were made. New or modified criteria were added [DDRE, 1993].

- Agent must be available in production quantities of at least 227,272 kg (500,000 pounds) per year by January 1, 1994.
- Cost approximately \$10 - \$12 per pound.
- Have an Ozone Depletion Potential (ODP) of 0.02 or less.
- Have an Acute Toxicity (as determined by rat 4-hour LC_{50}) less than Halon 1211.
- Have extinguishment performance comparable to Halon 1211 for 68 kg (150 lb) wheeled extinguisher (UL BC Rating = 160).

5.2.5.2 Screening

Based on the target criteria, screening criteria were developed for agent selection. The screening criteria included the following properties [Tapscott et al., 1991b].

- Cleanliness – Alternative firefighting agents must be clean. For this purpose the definition of clean is that the agent evaporates within a few minutes leaving negligible residue. Halocarbons with low to moderate boiling points are, in general, expected to meet this criteria.

- Toxicity – Measured or estimated acute toxicity of candidate agents must be comparable to or lower than that of existing halons.

- Fire Suppression – The agent must be effective in suppressing three-dimensional Class A and B fires. The agent itself should not be flammable at any concentration in air.

- Ozone Depletion Potential – The ODP should be less than 0.05 and as close to zero as possible.

- Global Warming Potential – The GWP of an alternative agent should be as close to zero as possible.

- Physical Properties – The agent should have appropriate physical properties for the application. An alternative streaming agent should have a boiling point comparable to existing streaming agents (approximately -10 degrees C to 60 degrees C). The vapor pressure at room temperature should be adequate to pressurize the container, but not to create a completely gaseous agent. A vapor pressure in the range of 0.35 - 2.8 kg/cm^2 (5-40 lb/in^2) is expected to be acceptable. For effective heat removal, an agent should have a high vapor heat capacity and high heat of vaporization. The vapor heat capacity should be greater than 0.09 cal/g- C (compared to 0.11 cal/g-C for both Halon 1211 and Halon 2402), and the heat of vaporization should be greater than 25 cal/g (compared to 32 cal/g for Halon 1211 and 27.6 for Halon 2402).

- Availability/Manufacturability – The agent should be able to be manufactured in bulk.

- Cost – The agent should be able to be manufactured at acceptable cost and will depend on the effectiveness and uniqueness of the agent. A highly effective agent that could be used in small quantities would be worth a higher price per pound than a moderately attractive agent that was less expensive.

- Materials Compatibility – The agent must be compatible with materials such as o-rings, valve seats and metals used in extinguishers. The test criteria include those described in ASTM tests for fluid resistance of gasket materials (ASTM F 146-84), hardness (ASTM D 1415-83), effects of liquids (ASTM D 471-479), change in length during liquid immersion (ASTM D 1460-81), physical properties of o-rings (ASTM D 1414-78), immersion corrosion testing of metals (ASTM G 31-72) and the examination and evaluation of pitting corrosion (ASTM G 46-76).

- Chemical Stability – An agent must be stable in long-term storage.

As with the Training Agent project, lists of near-term (Group 1), medium-term (Group 2) and far-term (Group 3) candidate agents were developed [Tapscott et al., 1991b]. The definition of the groups was the same as for the Alternate Training Agent work and initially the Group 1 agents were the same. However, the near-term agent list changed while this work was underway. Table 5 provides the complete list of Group 1/near term agents considered in the Flightline Agent work.

Table 5. Group 1 Candidates for Flightline Agent Work [Tapscott et al., 1991b]

HCFC-22	(CHF_2Cl)	HCFC-141bm	($C_2H_3FCl_2$)
HFC-23	(CHF_3)	HCFC-142b	($C_2H_3F_2Cl$)
HCFC-123	($C_2HF_3Cl_2$)	HCFC-143a	($C_2H_3F_3$)
HFC-124	(C_2HF_4Cl)	HFC-152a	($C_2H_4F_2$)
HCFC-134a	($C_2H_2F_4$)	PFC-318	(C_3F_8)

The researchers performed an extensive literature review to examine bond strengths, activation energies and rates of OH reaction [Tapscott et al., 1991b]. Methods for estimating activation energies were developed to assist in predicting atmospheric (tropospheric) lifetimes. As with the Alternative Training Agents work, this type of information was intended for use with prediction algorithms included in the NMERI Halocarbon Database. Due to the lack of information on agents included in Groups 2 and 3, the full screening was not performed on these groups [Tapscott et al., 1995]. Group 1 agents did not use the screening at all. The group 1 agents were selected solely on the basis of their commercial availability in bulk form and the presence of 'significant toxicity' studies. Perfluorohexane subsequently was added to the Group 1 list for this reason [ARA, 1998]. Halotron I subsequently was added to the list because it was a commercially available variant of the previously tested HCFC-123.

5.2.5.3 Laboratory-scale Testing

The laboratory-scale testing for Group 1 agents was based on the NMERI cup burner performance (a modified cup burner apparatus) and the boiling point of the agent [Tapscott et al., 1995]. The researchers reported that the agents showing the best extinguishment were second generation agents [Tapscott et al., 1995]. This presumably means from Group 2 or potentially Group 3. However, there was not enough technical information on these agents, particularly for toxicity, to allow their use in the near-term. From the Group 1 or near-term list, only two agents, perfluorohexane and HCFC-123 neat or in blends, showed promise as near-term replacements for Halon 1211. These agents showed a sufficiently high boiling point to enable their use in streaming applications. It was recommended that these two agents should be tested at intermediate-scale to determine if either meets the USAF requirements for a near-term Halon 1211 replacement.

In 1992, the USAF selected perfluorohexane as their leading candidate [Floden, 1992; DDRE, 1993]. Table 6 provides the list of the compounds and major problems the USAF reported with each at that time.

Table 6. List of Compounds Evaluated 1988 - 1992 [Floden, 1992; Tapscott et al., 1995]

Agent	Major Problem
HCFC-22	Poor streaming, high ODP, poor extinguishment
HBFC-22Bl	Unacceptable high ODP.
HCFC-123	High acute and chronic toxicity.
PFC-614	High cost, long atmospheric lifetime.
Blends of Above	Storage and handling problems.

5.3 U.S. Marine Corps Testing

5.3.1 Halotron I Testing

In 1992, the Crash Fire Rescue Branch, Marine Corps Air Station (MCAS) Beaufort, SC conducted fire tests with Halotron I, an HCFC-123 blend [MCAS, 1992]. The purpose was to compare the firefighting effectiveness of Halotron I to Halon 1211 in scenarios typically encountered on the flightline. Amerex handheld and 68 kg (150 pound) units were used. "Optimization" of the unit was performed. Seals, o-rings and nozzles were replaced and agent fill densities/operating pressures were modified. The results indicated that Halotron I was 34 percent less effective than Halon 1211 when considering agent weight, extinguishment time, agent flow rate and percentage used of available agent. On a weight basis, 38 percent more Halotron I was needed than Halon 1211.

An analysis was also performed to determine if the increased agent requirements would present a problem for firefighters [MCAS, 1992]. They reviewed data from the Naval Safety Center for January 1990 through May 1992. Their analysis revealed that on average when flightline personnel fight a fire they discharge (1) 79 kg (173 pounds) of Halon 1211 from two extinguishers, (2) 44 kg (96 pounds) of Halon 1211 from one extinguisher for the Navy, and (3) 72 kg (158 pounds) of Halon 1211 for the Marine Corps. Based on these data, they estimated that the same number of extinguishers would be needed for Halotron I as for Halon 1211. They concluded that Halotron I would be suitable for firefighting use.

5.3.2 Perfluorohexane Testing

It was reported by the manufacturer that tests with perfluorohexane were also performed by this same Marine Corps group during that same time period [Pignato et al., 1993]. Tests were performed with a 6.7 m^2 (72 ft^2) pan fire, engine nacelle fire, 3-D and pan fire and 75 m^2 (810 ft^2) pit (pool) fire. The manufacturer reported data indicated that perfluorohexane performed adequately.

5.4 USAF Full-scale Testing and Agent Validation (1993)

Based on the results from the two on-going USAF efforts, Alternate Training Agents and Flightline Agent, it was realized that candidates tested as potential training agents were of the same order of effectiveness as those tested to develop a flightline agent [Floden, 1992]. The two efforts were combined so that the agent suitable for flightline use would also become the training agent. The objective of this effort was to determine which agent was better, perfluorohexane or Halotron I [Floden, 1992]. It was hoped that one of these two agents would provide a demonstrable benefit over the other agent [Floden, 1992]. Four main activities were planned under this effort: (1) Operational Environment Tests; (2) 68 kg (150 pound) Extinguisher Optimization Tests; (3) Combustion Products and Operational Exposure Tests and (4) Materials Compatibility Tests [DDRE, 1993]. When the tests were completed, the final step in determining a suitable agent was to be EPA approval.

5.4.1 Operational Environment Tests (and 68 kg (150 pound) Optimization Tests)

5.4.1.1 Firefighter Training Test Series

The firefighter training program developed five fire extinguishment tests modeled after actual fire scenario conditions: spill fires, engine-mock-up fire, mixed fuel fires, electrical component overload fires and oxygen enriched aircraft interior fires [Lee and Tapscott, 1992].

Personnel at the HQ AFCESA/DF USAF Fire Protection Branch were involved in determining typical fire scenarios. The intent was that the test scenarios be representative of typical flightline fires and weather parameters.

The plan was for the candidate agents to be tested against a number of different types of fires, e.g., wood fires, hydraulic fluid fires, tire fires and other types of fuel fires [Lee and Tapscott, 1992]. Fire suppression tests would be conducted in varying weather conditions of rain, wind, heat and cold. It was recognized that the testing of agents should use applicable standardized tests. Some modifications, however, were recommended to provide realism and to lower costs. Parts of the UL standardized tests were modeled in the prescribed testing scenarios but the tests described were not standardized UL 1093 or UL 711 fire tests [Lee and Tapscott, 1993].

The results of these tests were to be used by the Chief of Air Force Fire Protection to certify or reject the agent for USAF-wide use [DDRE, 1993]. If the candidate agent were certified, AFCESA/DF would be responsible for implementing the agent throughout the USAF.

Four of the five tests scenarios were performed on Halon 1211 and perfluorohexane [Lee and Tapscott, 1993]. Three-dimensional running fuel fires were conducted in calm wind, 16 kpg (10 mph) cross wind and 16 kpm (10 mph) tail wind conditions with rain and extinguisher temperatures of -40 to 49 °C (-40 to $^+$120 °F). Aircraft wheel gear and spraying hydraulic oil fires, semi-enclosed electrical motor fires and semi-enclosed oxygen-enriched fuel fires were also performed.

The 7.0 m^2 (75 ft^2) 3-D fires were designed to simulate an aircraft engine fire where the fuel line has broken [Lee and Tapscott, 1993]. The test apparatus was identical to the one described under the Alternate Training Agents effort.

The aircraft wheel-gear apparatus consisted of an actual aircraft landing gear [Lee and Tapscott, 1993]. It contained the tire, wheel, brakes and landing strut/support braces. The hydraulic fuel was sprayed in a flat pattern toward the brake housing and tire. The semi-enclosed electric motor fire consisted of an 0.21 m^3 (11 ft^3) steel box with a removable lid partially covering the opening. A ½ horsepower motor was set-up to overheat when power was supplied. The semi-enclosed oxygen enriched fuel fire used the same 0.21 m^3 (11 ft^3) box as the electric motor fire test. An 46 cm (18-in) deep, 10.1 cm (4 in) high pan was filled with fuel and placed in the box. Oxygen was supplied directly into the fire. All of the tests were performed with Jet-A fuel (considered to be equivalent to JP-8). Four tests were run on each apparatus, 1 for Halon 1211 and 3 for perfluorohexane. Halotron I was not tested in this series.

The Amerex Model 600 68 kg (150 pound) extinguisher was used for all tests [Lee and Tapscott, 1993]. For the 3-dimensional tests under calm conditions, it required an average of 36 kg (80 pounds) of perfluorohexane and 9.6 kg (21 pounds) of Halon 1211 to extinguish the fires [Lee and Tapscott, 1993]. The cross wind and tailwind tests were more difficult for both agents. It required 43 kg (95 pounds) of perfluorohexane and 11kg (24 pounds) of Halon 1211 for the cross wind tests, and 46 kg (102 pounds) of perfluorohexane and 15.5 kg (34 pounds) of Halon 1211 for the tail wind tests. Under simulated rain conditions, both agents performed better; 35 kg (76 pounds) of perfluorohexane and 6.8 kg (15 pounds) of Halon 1211 were required. Under cold conditions, the perfluorohexane performance was increased. Eighteen kilograms (40 pounds) of perfluorohexane and 7.7 kg (17 pounds) of Halon 1211 were required. Several series were run at high temperature. A new nozzle was found to help to improve the high temperature performance of perfluorohexane. Thirty seven kilograms (81 pounds) of perfluorohexane and 11 kg (24 pounds) of Halon 1211 were required using the new nozzle.

The aircraft wheel gear fire used the Amerex Model 600 68 kg (150-pound) extinguisher with the original nozzle [Lee and Tapscott, 1993]. Both agents adequately extinguished the fire. It required 7.7 kg (17 pounds) of perfluorohexane and 2.7 kg (6 pounds) of Halon 1211. The semi-enclosed electric motor fire used a 9.0 kg (20 pound) handheld extinguisher. It required 1.4

kg (3 pounds) of perfluorohexane and 0.9 kg (2 pounds) of Halon 1211. The semi-enclosed oxygen-enriched fuel fire used the Amerex Model 600 68 kg (150 pound) extinguisher with the original nozzle. One and eight-tenths kgs (4 pounds) of perfluorohexane and 0.23 kg (0.5 pound) of Halon 1211 were required.

The researchers concluded that the effectiveness ratio of perfluorohexane to Halon 1211 was approximately 3-3½ to 1 under most conditions [Lee and Tapscott, 1993]. They suggested that perfluorohexane (1) "must be used in larger quantities during fire situations," or (2) "reserved for first response use only." It was also recommended that further testing be performed to optimize the nozzle system for delivery of perfluorohexane. Other than the nozzle change provided in this work, no other work was described in the literature that performed nozzle optimization tests with perfluorohexane.

5.4.1.2 FAA Sponsored Test Series

Another set of tests, sponsored by the FAA, was performed at Tyndall AFB in 1993 [Rochefort et al., 1993; ARA, 1998]. The test program was designed to quantify the fire extinguishment performance of perfluorohexane and Halotron I versus Halon 1211. While this test series consisted of "five unique fire extinguishment tests," these tests are different from those described above. The new five tests were (1) agent throw-range tests, (2) dry-pool fire extinguishment tests, (3) three dimensional inclined plane running fuel fire tests, (4) simulated engine-nacelle running-fuel fire tests and (5) simulated wheel-well fires involving hydraulic fluid. All tests except the wheel well fires used JP-4 as the fuel. The Amerex Model 600 68 kg (150 pound) extinguisher was used to dispense the agent in each test.

A report provided by the FAA describes the same test series and provides a general rationale for the test parameters for the work performed by the USAF [Wright, 1995]. The position of the FAA Technical Center Airport Technology R&D Branch was that any test protocol developed for evaluation of replacement clean extinguishing agent candidates should

duplicate as much as possible the original test scenarios for quantifying Halon 1211. The original tests were used by the FAA to qualify Halon 1211 as an acceptable alternative to PKP [Geyer, 1982]. A detailed description of the test series follows. For purposes of clarity in this review, the term "first series" will refer to the previously described USAF test series, the term "second series" to the FAA sponsored USAF test series, and the term "original FAA series" to the series performed by the FAA to qualify Halon 1211 versus PKP in 1982.

Dry-Pool Extinguishment Tests

Pool fire extinguishment tests are usually conducted by floating the fuel on a pool of water [Rochefort et al., 1993; Wright, 1995]. That type of test was not considered representative of most small fuel spill fires encountered in a flightline operation. A common scenario is the spillage of fuel on a dry, level concrete surface. The project manager of the test believed that using fuel over a substrate of water would be harder but was not indicative of fires encountered in a flightline fuel spill response. The test protocol was modified for dry pool fires only. The objective of the dry-pool fire test was to extinguish the fire as quickly as possible.

To simulate a pool fire, JP-4 fuel was poured onto a flat, level, 9.1 x 9.1 m (30 by 30 ft) concrete surface and ignited [Rochefort et al., 1993; Wright, 1995]. Fuel spill areas were varied between 23 x 74 m^2 (250 and 800 sq ft). It was found that the most expedient method for conducting the tests was to mark corners on the concrete and pour fuel on the concrete until it covered the desired area at which time ignition was made. This method resulted in fuel quantities of 26.5 to 57 ℓ (7 to 15 gallons). Other tests were run with known quantities of fuel, 38, 57, 76 and 95 ℓ (10, 15, 20 and 25 gallons) of fuel. The total pre-burn time for this test was not less than 20 seconds [Rochefort et al., 1993; Wright, 1995]. When the entire spill area was involved in fire, the fire was extinguished by an experienced firefighter.

While the stated intent was for the second series tests to duplicate the original FAA series, some important differences were present. The original FAA series allowed a minimum 20 second

pre-burn time after the peak fire intensity was reached as measured by radiometers [Geyer, 1982]. The original FAA series recorded data for both fire extinguishment time and fire control times. Fire control time was defined as the time to reduce the fire intensity to 0.2 Btu/ft^2-s. The original FAA researchers reported that fire control time was more consistently reproducible than extinguishment time. It does not appear that fire intensities were measured as part of the second series.

Another important difference that is related to fire intensity is the quantity of fuel. The original FAA series used 14.6 ℓ/m^2 (0.36 gallons per ft^2) of surface area. For a 10 m (33 ft) diameter pool 79 m^2 (855 ft^2), the quantity of fuel would be about 1,166 ℓ (308 gallons). This is significantly more fuel than for the second series. The original FAA series evaluated agents from a CFR vehicle and not from a portable extinguisher.

Work referenced in the original FAA series indicated that 73 percent of fuel spills are 15.1 ℓ (4 gallons) or less, 23 percent are 19 to 159 ℓ (5 to 42 gallons) and 4 percent are over 159 ℓ (42 gallons) [Geyer, 1982]. However, an analysis of the referenced work indicated that these fuel spills were for fueling operations only and would not be indicative of other types of mishaps [Ciccone and Graves, 1976]. The average spread of fuel associated with these spills was determined by work performed by the USAF in 1977 [Tapscott et al., 1996c]. It was determined in the original FAA series that 159 ℓ (42 gallon) spills would cover approximately 700 ft^2. Discharging 230 kg (507 pounds) of Halon 1211 at 139 kg/min (305 pounds per minute) was believed to be able to handle typical fuel spills [Geyer, 1982]. However, it must be noted that their analysis is not applicable to Halon 1211 portable extinguishers with a much lower flow rate.

Three-Dimensional Inclined-Plane Tests

The rationale for this fire test was that this scenario was believed to be common to many aircraft accidents [Geyer, 1972; 1982]. The test apparatus consisted of a 6.1 m (20 ft) long, 1.5 m (5 ft) wide steel ramp with a 1.2 to 2.4 m (4 x 8 ft) catch basin at the base [Rochefort et al.,

1993 and Wright, 1995]. The ramp was sloped at 1 inch per foot providing an 8.3 degree pitch. The steel ramp was overlaid with 3.8 cm (1.5 in) of concrete with the intent to be more consistent with original FAA tests. This was also reported to make the apparatus more representative of actual field conditions. JP-4 was discharged at the rate of 11 ℓpm (3 gpm) through five holes in the horizontal pipe positioned across the top of the incline. After 0.6 cm (0.25 in) of fuel accumulated in the catch pan, approximately 18.9 ℓ (5 gallons), the fire was ignited. Each fire was given a 30 second pre-burn time before attempting to extinguish.

The firefighting technique for all these tests was to initially extinguish the catch basin and drive the fire up the ramp toward the fuel spray bar. The firefighter was positioned on the windward side of the ramp. The test objective was to determine how long it took an experienced firefighter to extinguish the fire.

An important difference is noted between the second series and the original FAA series. The fuel flow rate of 11 ℓpm (3 gpm) used in these tests is significantly lower than the 23 to 45 ℓpm (6 to 12 gpm) used in the original FAA tests [Geyer, 1972; 1982]. It is not clear why the researchers chose to decrease the fuel flow rate. While the original FAA series test may be more severe, there is no indication that it is more or less representative of actual flightline events than the first series or second series of tests performed by the USAF. The event appears to simulate a crash on a runway. Although the general rationale was that this scenario was common to many aircraft accidents, it is questionable if it is applicable to the use of 68 kg (150 pound) or smaller extinguishers. The original FAA test series used a CFR vehicle and found that Halon 1211 could extinguish the 45 ℓpm (12 gpm) fuel rate event with available quantities and flow rates [Geyer, 1982]. It is also likely that a CFR vehicle responding to a crash would use AFFF as the primary agent and Halon 1211 as a secondary agent. If the intent was to lower the fuel rate to allow the Halon 1211 portable extinguisher to extinguish the fire, it is not clear how the 11 ℓpm (3 gpm) value was determined to be the correct value. No analysis was provided in the USAF or FAA literature that indicated that the 11, 23 or 45 ℓpm (3, 6 or 12 gpm) flow rate was indicative of actual conditions.

Simulated Engine-Nacelle Running-Fuel Tests

This test was designed to demonstrate the agent penetration and extinguishment capabilities for a full-size F-100 jet engine with added three-dimensional and pool fires [Rochefort et al., 1993; Wright, 1995]. A simulated engine nacelle for the F-100 engine was fabricated. The estimated internal volume of the nacelle was 5.4 m^3 (189 cubic feet). The slightly lower afterburner end of the engine nacelle test apparatus was unblocked to permit fuel to flow out of the nacelle, onto the concrete pavement. The flow rate was set at 19 ℓpm (5 gpm) and a 5 second pre-burn was used for all tests. The initial configuration utilized a 3.1 by 4.6 m (10 by 15 ft), 14 m^2 (150 square foot) curbed concrete area within the 9.1 x 9.1 m (30 by 30 foot) concrete pad, centered below the afterburner end of the nacelle. Due to leakage through the curb during the initial pre-tests, the curb sections were removed to allow the fuel to flow directly onto the 9.1 x 9.1 m (30 by 30 ft) concrete area. The test plan required 91 ℓ (24 gallons) of fuel to spill onto the concrete surface before ignition. This amount was used on initial second series tests but was eventually reduced to 57 ℓ (15 gallons) due to the severity of the 91 ℓ (24 gallon) fire.

Two important differences are noted between the second series and the original FAA series. The fuel flow rate is again lower, 19 ℓpm versus 30 ℓpm and 22 ℓpm (5 gpm versus 8 gpm and 6 gpm) [Geyer, 1972; 1982]. The pre-burn time is also different, 5 seconds for these tests versus 30 seconds for the original tests. The original FAA series test appears to be more difficult.

Simulated Wheel-Well Fire Involving Hydraulic Fluid

The test objective was to simulate a hot wheel brake and hydraulic fluid fire. The apparatus consisted of an F-4 aircraft tire and magnesium rim mounted on a stand inside a 1.2 x 1.2 m (4 by 4 ft) steel pan. A 7.6 ℓ (2 gallon) discharge of hydraulic fluid was placed inside the pan. One additional gallon of hydraulic fluid was poured on the tire itself and the fire was ignited. The most flammable Military Specification (MIL SPEC) hydraulic fluid specified for aircraft systems was used. As an additional safety precaution, the aircraft tire was deflated prior to

testing. A 90-second pre-burn was allowed before the firefighter would attempt to extinguish the fire.

Two important differences exist between this test and the original FAA series. The original test series (1) used sprayed JP-4 fuel instead of pouring hydraulic fluid over the tire and (2) it called for a 125 second pre-burn time [Geyer, 1982]. The original FAA test is likely a more severe threat.

Agent Throw-Range Tests

The effective throw range of the Amerex Model 600 68 kg (150 lb) extinguisher was assessed by discharging Halon 1211, perfluorohexane and Halotron I over a linear array of fire pans [Rochefort et al., 1993; Wright, 1995]. The 10 cm (4 in) tall, 28 cm (11 in) diameter pans were spaced 0.9 m (36 in) from center to center. Each pan contained 0.1 cm (0.25 in) of fuel 0.4 ℓ (13 oz.) floated on 1.3 cm (0.5 in) of water. Three and one-fourth inches of freeboard was maintained on the pans. Thirty seconds after the last pan was ignited, the agent was discharged from the fixed nozzle located 6.4 m (21 feet) from the first pan. The nozzle was positioned 0.8 m (32 in) above and parallel to the ground. The tests were conducted indoors to eliminate any effects of wind and the extinguishers were allowed to fully discharge. The test objective was to establish the maximum effective throw range for each candidate agent.

The test apparatus described in this work is considerably different from the original FAA work. The original FAA series used 52 0.3 m (1 ft) square pans and 32 aerial fire cans suspended at two horizontal levels [Geyer, 1982]. While not clear from the literature, it appears that the new series was modified because the original series was intended for use with CFR vehicles where the quantities and flow rates of agents are considerably higher. The original test series also evaluated the effect of the agents in combination with AFFF [Geyer, 1982]. No such tests were reported in the new series. In addition, the first series of full-scale tests performed by the USAF showed that

a side to side motion nozzle worked well for perfluorohexane [Lee and Tapscott, 1993]. This set (second series) used a fixed nozzle.

5.4.1.3 Results and Conclusion

The researchers for the USAF concluded that Halotron I was slightly more effective than perfluorohexane on average [Rochefort et al., 1993]. Halotron I and perfluorohexane showed equal performance on dry-pool fires and the simulated engine nacelle running fire. Perfluorohexane performed better than Halotron I on the agent throw range tests. Halotron I performed much better that perfluorohexane for the three-dimensional inclined plane and the simulated wheel well tests. The FAA researchers concluded that Halotron I was capable of extinguishing the flightline fire types originally designed for testing Halon 1211. The FAA researchers also reported that perfluorohexane could not extinguish the engine nacelle running fuel fire, but noted that the delivery systems were not fully optimized in the early test program [Wright, 1995]. Based on these tests, the FAA reported that the effectiveness ratio of Halotron I to Halon 1211 is approximately 1.5 to 1 [Wright, 1995]. It is unclear how this value is comparable to the effectiveness ratio of 3-3½ to 1 for perfluorohexane to Halon 1211 previously reported by the USAF for the first series [Lee and Tapscott, 1993].

5.4.2 Combustion Products and Operational Exposure Tests

Tests were performed in the Fall of 1991 to assess the exposure of firefighters during training exercises [Cowherd, 1995]. Halon 1211, HCFC-123, and perfluorohexane were used to extinguish JP-4 fires. The test apparatus used the simulated 3-dimensional apparatus developed for the Alternate Training Agent effort (and not the one for the FAA sponsored tests) [Floden, 1992]. Firefighter exposures, downwind depositions, and the chemical combustion products were measured with an FTIR for fuel-only fires and fires with applied agents [Cowherd, 1995]. It was reported that the data was to be used to develop the dose portion of the dose-response model for the firefighter risk assessment [Floden, 1992]. The initial results indicated that the acid gases

generated by all three agents were above the Immediately Dangerous to Life and Health (IDLH) values down-wind of the fire [Cowherd, 1995]. Instantaneous concentrations exceeded the IDLH by 10 times for COF_2. As a result of this work, it was recommended that all halocarbon based extinguishing agents should only be used by trained personnel. This presumably includes Halon 1211. It is unclear how the recommendations of this work were used by the USAF.

In addition to the fire tests depicted above, toxicity studies were described as being performed to determine the response portion of the dose-response model for the firefighter risk assessment [Floden, 1992]. These studies were to be performed at the USAF Armstrong Laboratory. The purpose of this work was to determine if there was any indication of a toxic response due to the exposure of a firefighter to alternative agents during a typical training scenario.

5.4.3 Materials Compatibility

An evaluation was performed to determine the effect of perfluorohexane on a wide range of materials. Extinguisher seals, gaskets, hoses and tanks were tested for any reaction with the agent. Other materials which may come in contact with the agent during firefighting were also reviewed [Floden, 1992]. The material compatibility tests were conducted according to applicable UL and American Society for Testing and Materials (ASTM) test methods [Lee and Tapscott, 1992; 1993]. The testing showed that perfluorohexane was compatible with most elastomers, metals, composites, coatings and electrical components found on aircraft. Teflon and silicone rubber were exceptions.

5.4.4 Environmental Impact Analysis

The USAF approach to the environmental analysis was to wait until the final candidate agent had been identified before performing an environmental impact analysis [Floden, 1992]. The analysis would consider the fate and effect of the agent when used as a firefighting agent. All

possible releases of the agent to the environment would need to be considered in the analysis. The results of this work would be the necessary documents to obtain approval to field and use the new agent.

5.4.5 Outcome of Agent Validation and Full-scale Testing

Based on the field-scale fire tests the FAA chose Halotron I as the leading agent to replace Halon 1211 [Wright, 1995]. The FAA reported that EPA restrictions placed on perfluorohexane for commercial airport firefighting use limited their evaluation. Since the final report from the FAA was not published until October 1995, it appears that the decision to choose Halotron I was based solely on the EPA restriction and not on any performance differences between the two agents. It does not appear that the firefighter exposure tests and the material compatibility tests performed years earlier by the USAF were used by the FAA. No reference is made to these tests in the FAA decision to recommend Halotron I. No requirement to perform similar tests is contained within the draft FAA Advisory Circular for Aircraft Fire Extinguishing Agents [FAA, undated]

Based on the FAA sponsored field-scale testing, the USAF reported that Halotron I performed slightly better than perfluorohexane [Rochefort et al., 1993]. The other tests performed by the USAF either did not include (1) Halotron I or (2) a direct comparison between perfluorohexane and Halotron I. However, the USAF chose perfluorohexane as their leading candidate to replace Halon 1211 for training and actual firefighting use [Floden, 1992; DDRE, 1993]. Due to the very high atmospheric lifetime of perfluorohexane, the EPA placed restrictions on its use [EPA, 1994]. While no restriction was placed on its use for actual firefighting, the USAF did not field this chemical.

While neither Halotron I nor perfluorohexane was deemed ultimately acceptable for fielding by the USAF, the clean agent requirement was re-validated [Leonard et al., 1992;

DDRE, 1994]. A new program was developed to find a Halon 1211 replacement: The Advanced Streaming Agent (ASA) Program [DDRE, 1994]

5.5 The Advanced Streaming Agent (ASA) Program (1993 - present)

In 1993, the USAF performed an evaluation to validate the requirement that a clean agent is needed for flightline firefighting [DDRE, 1994]. As part of the re-validation process, work was carried out to determine the possible extent of collateral damage that would be caused by a "dirty" secondary agent [Leonard et al., 1992]. It was found that 95 percent of the reported fires are small fires where the need to limit collateral damage is greatest. The estimated damage per incident was $12,600 when a clean agent, i.e., Halon 1211 was used. The remaining 5 percent were large fires with an estimated $1,405,337 of damage per incident. The agent most frequently used in these unreported events was Halon 1211. A series of analyses were performed to determine the collateral damage costs if a dirty agent such as PKP were used instead of a clean agent. It was estimated that the annual costs for engine repairs due to collateral damage could be as high as $40,500,000 per year.

While the ASA program has been on-going since 1994, there is little information available in the literature on the progress and results to date. Literature cited in conferences and proceedings papers are as of yet unpublished. Table 7 lists these references. The available literature has been reviewed and is summarized below.

Table 7. Cited ASA Program References that are Unavailable

Tapscott, R. E., et al., Advanced Agent Reference Database Description, Advance Agent Working Group, January 1996.

Tapscott, R. E., and Lee, M. E., Halocarbons as Halon Replacements: Medium-scale Testing of Halon 1211 Replacements, ESL-TR-89-38, Vol. 5 of 5, Wright laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, May 1993. NMERI SS 2.03(5)

Skaggs, S. R., and Tapscott, R. E., Advanced Streaming Agent Program, Interim Letter Report, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, July 1994. NMERI OC 94/38.

Lifke, J. L., Moore, T. A., Tapscott, R. E., and Heinonen, E. W., Advanced Streaming Agent Development, Phase IIA: Medium-scale Testing of Advanced Agent Compounds, WL-TR-96-XX, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, November 1996. NMERI 96/14/32760

Lifke, J. L., Moore, T. A., Tapscott, R. E., Heinonen, E. W., and Kaizerman, J. A., Advanced Streaming Agent Development, Phase IB: Syntheses, Toxicity, and Decomposition Products, WL-TR-96-XX, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, November 1996. NMERI 96/13/32760

Tapscott, R. E., et al., "Advanced Streaming Agent Development, Volume I: Silicon Compounds", WL-TR-96-XX, Vol. 1 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

Tapscott, R. E., et al., "Advanced Streaming Agent Development, Volume II: Metal Compounds", WL-TR-96-XX, Vol. 2 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

Tapscott, R. E., et al., "Advanced Streaming Agent Development, Volume III: Phosphorus Compounds", WL-TR-96-XX, Vol. 3 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

Tapscott, R. E., et al., "Advanced Streaming Agent Development, Volume IV: Tropodegradable Halocarbons", WL-TR-96-XX, Vol. 4 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996.

Lifke, J. L., Moore, T. A., and Tapscott, R. E., Advanced Streaming Agent Development, Volume V: Laboratory-scale Streaming Tests, WL-TR-96-XX, Vol. 5 of 5, Wright Laboratories (WL/FIVCF), Tyndall Air Force Base, Florida, and Applied Research Associates, Inc., Tyndall Air Force Base, Florida, June 1996. NMERI 96/2/32540

The objective of the ASA program is to develop and evaluate a new agent that will exhibit equal or improved performance as compared to Halon 1211 [Skaggs et al., 1993]. A program work plan was developed in late 1993. It separated the work into four sections: (1) identify candidates, (2) collect/provide additional chemical and physical properties, (3) medium- and full-scale fire extinguishment testing, toxicology properties, and materials compatibility and (4) operational validation testing. The technical approach was to tailor the program for firefighting needs of the military for flightline applications. As with previous work, a parallel path approach was chosen so that simultaneous evaluations could occur.

5.5.1 Identify Candidates

It was proposed in the ASA work plan that an expert panel be established to provide advice on the work to be performed and to review the project progress [Skaggs et al., 1993]. The panel would consist of approximately six members in addition to NMERI personnel in the areas of global environmental issues, toxicity, fire suppression science and synthesis and manufacturability. These experts would review the technical approach, data collection procedures, interpretation of results and environmental, regulatory and safety issues that may have an impact on agent viability. In addition, the panel would review and recommend to the USAF the criteria that will be used to select chemicals as candidate agents. This review panel subsequently became known as the CF_3I Ad Hoc Working Group [ARA, 1998]. Since that time, this group has changed its name to the Advanced Agent Working Group.

The method proposed to identify potential candidates was to review fire suppression mechanisms to support the development of predictive algorithms to estimate the fire suppression capability of compounds [Skaggs et al., 1993]. A broad list of candidates would be developed for consideration. The initial types of compounds considered were bromofluoroalkenes, fluoroiodocarbons, aromatic bromine- or iodine-containing halocarbons, polar-substituted bromocarbons, haloalkyl amines and phosphonitriles.

5.5.1.1 Requirements and Selection Criteria

The intent was to identify a list of candidates based on combined properties that were expected to enhance extinguishment and reduce atmospheric lifetime [Tapscott and Skaggs, 1994]. Table 8 provides the list of chemical families and the rationale for their choice. Nearly 100 potential candidates were identified that fall into four basic chemical classes: silicon containing compounds, metals, phosphorous containing compounds and tropodegradable halocarbons.

Table 8. ASA Chemical Families and Rationale [Tapscott and Skaggs, 1994]

Enhance Flame Extinguishment	Reduce Atmospheric Lifetimes
Bromine	
Iodine	Iodine
Metals	Metals
Sulfur *(Suspected)*	Sulfur
Phosphorous *(Suspected)*	Phosphorous
Epoxides *(Suspected)*	Epoxides (*suspected)*
Nitrosyls (NO) *(Suspected)*	Nitrosyls
	Silicon
	Unsaturated Double Bonds (C=C)
	Aromatics
	Carbonyl groups (-C(O)-)
	Hydroxyl groups (OH)
	Ether linkages (-O-) (*suspected)*
	Amines/amides/morpholines (suspected)

It was intended that the initial list of specific chemicals would be generated from this broad list based on information collected on manufacturability, toxicity, environmental issues, physical/chemical properties and other relevant information. The collected data would be compared to created selection criteria in a Weighted Attributes Candidate Assessment Matrix (WACAM) process. Those chemicals which best met the selection criteria would be selected for further evaluation. The defined selection criteria are provided in Table 9 [Tapscott and Skaggs, 1994].

Table 9. ASA Candidate Selection Criteria (Requirements)

Physical Properties	Boiling Point Melting Point Vapor Pressure	> -10 °C < -60 °C (≅ 1 kPa) @ 0 °C
Chemical Stability	Thermal Decomposition	< 1% per year @ 125 °C
Toxicity	Acute	Most sensitive toxic endpoint threshold > extinguishing concentration
	Chronic	Non-carcinogenic
Manufacturability	Availability Cost	Known synthetic routes < $50/lb.
Cleanliness	Corrositivity Electrical Conductivity	Non-corrosive @ 125 °C Agent and decomposition products not electrically conductive.
Extinguishment	Cup Burner Concentration	Halon 1211 (≅ 3% vol)
Environmental Impact	Atmospheric Lifetime Ozone-Depletion Potential	< 1 year < 0.001

These criteria were not intended to be used as pass/fail criteria. Instead, they would provide guidance on the choice of chemical families [Tapscott and Skaggs, 1994]. Although the original plan was to use WACAM to screen the chemicals to be selected for further evaluation, specific information needed to make the comparison was missing for many chemicals. A representative candidate from each chemical family was chosen to test for extinguishment effectiveness using a cup burner apparatus. The selection was based on the availability of a chemical/chemical family, only excluding those families of chemicals that had environmental restrictions. The initial list of candidates selected for further study is provided in Table 10; additional compounds will be added as research continues or additional families of chemicals are identified.

Table 10. Initial List of ASA Candidate Agents [Tapscott and Skaggs, 1994]

Name	Formula	Phase	CAS No.	Boiling Pt. °C
2-Bromo-3,3-diifluoropropene	$CH_2=CBrF_3$	Liquid	420-90-6	42.0
2-Bromo-3,3,3-trifluoropropene	$CH_2=CBrCF_3$	Liquid	1514-82-5	34
Bromopentafluorobenzene	C_6BrF	Liquid	344-04-7	137
Trifluoroiodomethane	CF_3I	Gas	2314-97-8	-23
Heptafluoro-1-iodopropane	C_3F_7I	Liquid	754-34-7	41
Heptadecafluoro-1-iodooctane	$C_8F_{17}I$	Liquid	507-63-1	160.5
Octafluoro-1,4-diiodobutane	$CF_2ICF_2CF_2CF_2I$	Liquid	375-50-8	85
Bis(cyclopentadienyl)iron II	$Fe(C_5H_5)_2$	Solid	102-54-5	249
Hexafluoro-1,3,5,2,4,6-triazatriphosphorine*	$N_3P_3F_6$	Liquid		
Hexafluoro-1,2,2-epoxypropane	C_3F_6O	Gas	428-59-1	
Bis(trifluoromethyl)nitroxide	$(CF_3)_2NO$	Gas	2154-71-4	-25

* Also contains various quantities of $N_3P_3F_5Cl$, $N_3P_3F_4Cl_2$, and $N_3P_3F_3Cl_3$

It was recommended that additional clarification be made for two elements in the screening criteria: cleanliness and toxicity [Tapscott and Skaggs, 1994]. It was recognized that no measure of 'how clean is clean' existed. Some of the potential candidates may not be as clean as Halon 1211 but may be perfectly suitable. Further specific definition of cleanliness was needed. A similar problem existed with the toxicity criterion. It was recommended that definitive studies be performed to determine the level of toxicity that is acceptable in typical use scenarios. They recognized that candidates with higher or differing toxicity characteristics might be acceptable but would be ruled out using the established criterion.

The work plan included tasks that were expected to have been completed already [Skaggs et al., 1993; DDRE, 1994; DDRE, 1996; DDRE, 1995]. These tasks are involved in identifying and reducing the number of candidates. Candidates for large-scale testing were to be

selected at the end of FY 96. It is assumed that the unavailable reports will provide information on these tasks once published. A summary of the ASA program proposed USAF work follows [Skaggs et al., 1993].

5.5.2 Collect/Provide Additional Chemical And Physical Properties

5.5.2.1 Manufacturabiltiy and Synthesis

This work will assess the manufacturability of candidate streaming agents [Skaggs et al., 1993]. If commercial sources are not identified, then synthetic mechanisms will be proposed. The manufacturability assessment will include estimates of agent cost, production requirements, and time required for production. A manufacturability index will be determined to provide an indication of the potential for the chemical to be produced in bulk quantities.

5.5.2.2 Global Environmental Impact Assessment

All available information on global, terrestrial and aquatic environmental characteristics will be collected on the broad list of chemicals [Skaggs et al., 1993]. Data on atmospheric lifetimes, ODP, GWP and environmental fate will be collected or estimated. For those candidates that appear promising, rigorously calculated ODP and GWP values may be determined. Other environmental impacts, particularly for aquatic environments, will be assessed.

5.5.2.3 Toxicity Evaluations

A toxicity assessment will be conducted to compile all available data and estimates of toxicological indices on candidate agents [Skaggs et al., 1993]. This preliminary evaluation is needed to avoid spending resources developing compounds that ultimately will not get used. Concerns expressed by the USAF, EPA and others about appropriate endpoints will be considered in this assessment.

5.5.2.4 Laboratory-scale Testing

It was planned that the NMERI cup burner data and LSDE data be developed for all of the candidates [Skaggs et al., 1993]. Baselines for a modified LSDE will be developed using Halon 1211, HCFC-123 and perfluorohexane, and used to assess the candidate agents. In addition, FTIR Spectrometry will be used to measure decomposition products as a function of agent application rates, fire size and fuel type.

It was expected that the USAF would down-select to three to five agents when the above work was completed [Skaggs et al., 1993]. These down-selected agents would undergo further testing and evaluation. However, the level of funding anticipated at that time only allowed one agent to proceed instead of the three to five proposed.

5.5.3 Medium- and Full-scale Tests, Toxicology Properties and Materials Compatibility

5.5.3.1 Additional Toxicity Evaluation

For candidates lacking known acute toxicology data, toxicity tests will be performed in conjunction with USAF Armstrong Laboratory [Skaggs et al., 1993]. An adaptation of the US EPA acute inhalation "limit test" will be used as a preliminary assessment method. Gas uptake studies and biological partition coefficients will be determined for use in pharmiokinetic modeling.

5.5.3.2 Physical/Chemical Property Analysis

The missing properties required to perform a full feasibility evaluation will be determined [Skaggs et al., 1993]. Room temperature density and vapor pressure measurements between 60 and 71°C (160 °F) will be measured.

5.5.3.3 Chemical Stability

The chemical stability of candidate agents will be evaluated in a series of six month stability tests at 27°C to 77°C (80°F and 170°F) under ambient and 24 atm (360 psi) N_2 pressure [Skaggs et al., 1993].

5.5.3.4 Toxicological Evaluation

The specific toxicity tests required would be coordinated with the USAF, other military services, U.S. EPA and other authorities having jurisdiction [Skaggs et al., 1993]. Possible tests needed were expected to be LC_{50}, cardiac sensitization (NOAEL or LOAEL), 90 day sub-chronic test and developmental toxicology. Candidates with little or no toxicity data will require a larger effort. The toxic properties of combustion byproducts will also be determined. Exposure scenarios will be compared to expected quantities of emissions to perform a risk assessment.

5.5.3.5 Medium-scale 0.4 to 3 m (4 to 32 ft^2) and Full-scale Testing 7 to 14 m^2 (75 to 150 ft^2, and 3-D)

The most promising agents will be evaluated concurrent with the toxicity evaluations [Skaggs et al., 1993]. The intent is to use the test procedures and facilities established under previous research efforts. Based on the description, it is assumed that the tests are the same used for the MNGP - Alternate Training Agents work, Sections 5.2.3.3 and 5.2.3.4. Previously collected Halon 1211 data will be compared to the new candidate agents.

5.5.3.6 Materials Compatibility

The most promising candidate agents will be tested with USAF flightline weapons system materials such as composites, exotic metals, electronics, plastics and seals. Testing will be conducted in accordance with UL 1093 [Skaggs et al., 1993]. The specific test method would

appear to be the same used for the previous MNGP - Full-scale Testing and Agent Validation, Section 5.4.3.

5.5.4 Operational Validation Testing

The work plan called for testing to be conducted in various weather conditions and against several fire types [Skaggs et al., 1993]. Temperature and moisture extremes were planned to be included in the test matrix. The fire types and scenarios included engine nacelle mock-up, landing gear materials (rubber, magnesium, steel, etc.), computer components and wiring harnesses. The stated objective is to compare the new agents against the previously developed results for Halon 1211 [Skaggs et al., 1993]. Based on that statement, it would appear that the intent is to use one of the two series previously sponsored by the USAF. Based on the limited description of the tests, it would seem more likely that it is close to the series developed by AFCESA/DF and not the one developed by the FAA.

5.5.5 USAF Results Reported to Date

It was reported that field-scale experiments were conducted by the USAF to evaluate CF_3I as a streaming agent [Tapscott et al., 1996a]. The initial results were promising but concerns were raised that the No Observed Adverse Effect Level (NOAEL) for CF_3I is below that of Halon 1211, i.e., did not meet the selection criterion. Work was initiated on CF_3I and other fluoroiodocarbons to determine if blending these agents with low toxicity agents would improve the toxicological characteristics of the blend. Based on their assessment of toxicity, existing and "likely" regulatory restrictions and availability of potential blending agents, it was concluded that only HFCs should be considered. Cup burner data were generated for CF_3I blends with HFC-125, HFC-134a, HFC-227ea and HFC-236fa. Two types of cup burner data were generated, NMERI 5/8-scale and the liquid agent cylinder method.

The study reported that no more than 40 percent CF_3I may be contained in a blend in order to meet the requirement that the NOAEL of the agent be equal or higher than that of Halon 1211 [Tapscott et al., 1996a]. This value was, however, only based on an assessment. No toxicity testing was performed to determine potentiation between the CF_3I and the blending agents. It was also reported that the extinguishing concentrations for 40 percent CF_3I blends with HFC-227ea and HFC-236fa range from slightly higher than that of neat CF_3I to significantly lower [Tapscott et al., 1996a]. An analysis of their data indicated that there was a high level of scatter present and significant differences in results were reported for the tests performed by NMERI versus Tyndall AFB. It was concluded by the researchers that the blends with HFC-227ea and HFC-236fa appear most likely to meet the USAF streaming agent requirements [Tapscott et al., 1996a]. It was recommended that these blends continue in further laboratory- and field-scale testing and that toxicity assessments be conducted.

Work is proceeding on the silicon compounds, metals, phosphorous compounds and the tropodegradable halocarbons to provide chemical and physical data. The reports for the silicon compounds, metals, phosphorous compound and tropodegradable halocarbons are still in draft form and are not available in the open literature. The only published information available indicated that laboratory synthesis of phosphonitriles has been completed, and efforts are under way to synthesize large quantities [DDRE, 1996]. Cup burner data have also been established for the phosphonitriles. The USAF reports that these compounds have lower extinguishing concentrations than Halon 1211 and CF_3I.

A general update and information on the classes of compounds was presented at the 1996 Halon Technical Options Working Conference and at a meeting in June 1996 [Tapscott et al., 1996b; Hellwig, 1996]. The USAF reported that the ASA program will be completed in FY98 and it is anticipated that a suitable replacement will result. However, no information was provided on specific chemicals that appear to be promising in the near-term.

5.6 United Kingdom Civil Aviation Authority

The U.S. Federal Aviation Regulations (FAR) /Joint Aviation Regulation (JAR) requires that Halon 1211, or equivalent, handheld extinguishers be installed on all commercial aircraft [14CFR, 1991]. The regulation "allows" that agents other than Halon 1211 may be used if they are demonstrated to be appropriate for the kinds of fires likely to occur [Chattaway, 1995]. The current draft "Minimum Performance Criteria for Replacement Hand Held Portable Extinguishers for Aircraft Cabin Fire Protection" lists the kinds of fires as (1) transport and commuter type aircraft cabins, (2) lavatories, (3) accessible baggage compartments and (4) flightdecks (i.e., cockpit) [FAA, 1996]. This document does not provide any additional information on specific threats. It does require that the extinguisher contain an agent with a Class A capability and meet the minimum UL 5BC or BS 5423 3A35B rating (or equivalent). It also requires that the extinguisher meet the minimum performance of the Hidden Fire Test and the Arson/Highjacking Threat test.

The UK CAA sponsored a study to develop a test method to quantify the capabilities of Halon 1211 for hidden fires [Chattaway, 1995]. Although Halon 1211 extinguishers were not originally required by the FAA or JAA for this purpose, this capability has become a requirement in finding a Halon 1211 replacement. Actual firefighting events on in-flight aircraft have demonstrated the need for an agent to fight fires that may be hidden behind the cabin wall or below the floor.

The CAA sponsored study developed an apparatus that was comprised of 5 arrays of 4 - 35 mm heptane fires, with baffles to represent obstructions [Chattaway, 1995]. A Walter Kidde brand Halon 1211 extinguisher was used as a baseline to determine where and how many of the pan fires were extinguished in the test apparatus. A sensitivity analysis was performed by altering the Walter Kidde in terms of quantity of agent and nitrogen gas (N_2) pressure. Halon 1211 extinguishers from other manufacturers were evaluated that use different Halon 1211 quantities

and N_2 pressures. The results for the number of fires extinguished was found to correlate with the agent quantity and mass flow rate.

Once the baseline was established, several halon alternative agents were evaluated: FE-25, FM-200, CEA-410, CEA-614 and Triodide [Chattaway, 1995]. Each agent was tested with a discharge time of 10 +/- 1 second, to be consistent with the Halon 1211 units tested. The quantity of the alternative agent was determined based on the agent's cup burner value with respect to Halon 1211. It was clearly recognized that this apparatus was a better measure of the total flooding capability of the agent than the streaming capability of the agent. Not surprisingly the lowest boiling point agent, FE-25 performed the best extinguishing the most fires, and the highest boiling point agent, CEA-410, extinguished the least. The researchers reported that Triodide, a chemical acting agent, did not perform as well as may have been expected based on its boiling point and cup burner value.

An analysis was performed for the space and weight implications of the four replacement extinguishing units based on the cup burner values [Chattaway, 1995]. On average, they suggested that twice the weight of the physical agents would be required and only about 6 percent more for Triodide. The volume requirements range from 1.88 for FE-36 to 2.9 times that of Halon 1211 for FE-25. However, it does not appear that this analysis was based on the same number of fires extinguished, i.e., same level of performance. For example, the value cited for FE-25 is for extinguishing 65 percent of the test fires versus only 48 percent for Halon 1211. A similar situation exists for the weight of the agents. When FE-36 is compared to Halon 1211, both extinguish about 50 percent of the fires, the weight is less than 1.4 times that of Halon 1211. As of October 1996, no pass/fail criteria had been developed for this test.

5.7 Commercial Industry Efforts

A number of companies have been and continue to be actively engaged in the development and testing of Halon 1211 replacement agents for use in portable and wheeled fire extinguishers. These systems are now becoming available [Huston, 1996b]. Commercial industry has obtained Underwriters Laboratories Inc. (UL) ratings for extinguishers using Halotron I, FE-36, FE-241 and FM-200. In addition, FE-241, NAF P-III, Triodide and CEA-614 are all recognized as acceptable alternatives to Halon 1211 on the EPA SNAP list.

5.8 Current Status

Since at least 1988, the USAF, USMC and commercial industry have been evaluating chemicals for the near-term replacement of Halon 1211. In only one case has a flightline agent been approved for use. Halotron I has been approved by the FAA as an acceptable secondary agent on FAA regulated flightlines. Smaller hand-held extinguishers with FM-200 and FE-36 have received UL listing, but based on the available literature, no systematic evaluation has been conducted for their use on military flightlines and Naval flight/hangar decks.

6.0 ASSESSMENT OF RDT&E EFFORTS

In the development of the MNGP, it was proposed that three approaches were needed to find a suitable alternative for all uses of Halon 1211: (1) use new engineering methods based on risk and cost/benefit analysis to evaluate the need for a clean agent such as Halon 1211 or a replacement; (2) develop new or modified hardware that can decrease the reliance on halon use, thus decreasing the reliance on halon and (3) develop an alternative or replacement agent [Tapscott et al., 1987e]. Approach 1 was performed in 1992/1993 to re-validate the clean agent requirement for engine fires as part of the ASA program. Prior to that time only work related to finding an alternative agent was found in the literature. This work identified the requirement to

find a drop-in alternative agent for Halon 1211 [Tapscott et al., 1991b; DDRE, 1993]. While the available literature for the ASA program does not necessarily provide the requirement that the agent perform as a drop-in, the work plan proposes that Halon 1211 will be used as a baseline to evaluate any new agents [Skaggs et al., 1993]. As in previous work, emphasis is placed on the capabilities of Halon 1211.

The screening criteria for the MNGP Flightline Agent work included three-dimensional Class A and B fires [Tapscott et al., 1991b]. However, the target criteria listed the requirement as the ability to meet a UL BC Rating of 160 [DDRE, 1993]. This is the only case where a firm fire extinguishment capability was required. Halon 1211 150 pound extinguishers have a UL rating as high as 30A240BC. It appears, from the reviewed literature, that detailed operational requirements for flightline fire extinguishing equipment have been lacking in previous Halon 1211 replacement efforts. The lack of operational requirements for flightline fire extinguishing equipment has negatively impacted the search for Halon 1211 replacements in all phases of research and development.

7.0 CONCLUSION AND RECOMMENDATIONS

The majority of the work sponsored or performed by the USAF, FAA, USMC and commercial industry to find Halon 1211 alternatives centered on finding replacement agents that would work as well as Halon 1211 in existing equipment. This is particularly true of the early efforts. The requirement was to develop an agent(s) that was "volumetrically equivalent," i.e., the drop-in approach. This approach has helped to identify Halon 1211 alternative agents for some applications; however, it has yet to identify a suitable Halon 1211 replacement for military flightlines and flight decks.

Later efforts by commercial industry have been focused on developing Halon 1211 alternative systems from the commercially available agents to obtain suitable UL ratings for

commercial use. In this approach, the "operational requirement" is for the system to extinguish the appropriate fires to receive the required UL ratings. The requirement is not based on the performance of Halon 1211 systems nor is it constrained to volumetric equivalence with Halon 1211. This approach has resulted in the development of new extinguishers based on Halotron I, FE-36, FM-200 and water mist. While on both a volumetric basis and an overall system weight basis these systems generally do not perform the same as Halon 1211, they perform adequately to meet or exceed the performance requirements, i.e., extinguish the fires prescribed by the UL rating system.

From the available literature, it appears that the ongoing R&D in the USAF ASA, 1998 program is using a similar approach for evaluating the potential suitability of a new generation of Halon 1211 replacement agents. While the drop-in agent approach may be ultimately successful in finding a Halon 1211 replacement, it is unlikely that it will be in the near future. If it is determined that the U.S. Navy requires a near-term, clean, secondary agent to replace or augment Halon 1211 for flightline and flightdeck use, it must rely on current commercially available agents. It is recommended that the systems engineering approach performed successfully by commercial industry be adopted by the U.S. Navy in evaluating near-term systems and agents for flightline and flightdeck use.

The two clean agent replacement chemicals that are currently available for evaluation are HFC-227ea and HFC-236fa. These agents are similar to perfluorohexane in extinguishing capability. While both of these agents will not perform as well as Halon 1211 based on the cup burner and may not perform quite as well as a streaming agent, it is possible that they may perform well enough to meet defined firefighting needs on the flightline and flightdeck. Both HFC-227ea and HFC-236fa are being commercialized in portable extinguishers with adequate UL ratings to replace Halon 1211 extinguishers in commercial applications. These commercially available systems should be evaluated against the defined fire threat on the flightline and flightdeck to determine if they meet or exceed the requirement.

It is recommended that the operational requirements for a clean, secondary agent be determined for flightline and flightdeck use. The analysis would need to include (1) the types of fires, e.g., engine wet starts, 3-D cascading fire, hot wheel brake, and on-board electrical, (2) the types and flow rates of fuel and (3) the maximum size of a pool fire that a clean, secondary agent needs to extinguish on the flightline and flightdeck when used as first-aid attack. Based on the operational requirements, test methods, procedures and parameters should be developed that will assess the ability of candidates to meet or exceed these requirements. The evaluation should be performed against strict pass/fail criteria that are related to one or more aspects of the operational requirements. Tests may also be developed to evaluate the candidates in scenarios that would be "nice-to-have" but not required, to assess their effectiveness and provide guidance to firefighters.

The development and documentation of operational requirements, appropriate tests and strict assessment methods would allow for the evaluation of near-term and longer-term agents. This course of action would also make it easier to re-evaluate the fire threats, change tests, and update assessment methods as circumstances and materiel change in the future.

8.0 REFERENCES

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